Effect of Tensile and Compressive Pre-Strains on Superelastic Diamond Surrogates

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Tom Duerig
Tension – Tension ($0 < R < 1 ; \varepsilon_M \neq 0$)

Shamimi et al., SMST 2015

Ni$_{50.6}$Ti$_{49.4}$ Wire 0.22 mm Diameter
Af: 8°C
Mean Strain 2%
Test Temperature 37°C
Rotary Bend Fatigue (R = -1 ; \( \varepsilon_M = 0 \))

Rotary Bend Fatigue ($R = -1 ; \varepsilon_M = 0$)

Shamimi et al., Unpublished Data
Objective

Determine whether residual stresses are the primary mechanism for durability improvement in Nitinol
Origins of Residual Stresses

- Localized yielding from a surface notch or from a multi-axial stress state (Bending, Torsion etc.)
- Microstructural inhomogeneities (Presence of inclusions)
- Grain orientation in a poly-crystalline material
Computational Modeling of Residual Stresses under
• Bending load (diamond specimens)
• Presence of inclusions (tension specimens)

Test Results of Pre-strain Diamond Study
• Test Methodology
• Baseline without pre-strain on diamonds
• Effect of tensile pre-strain on fatigue life
• Effect of compressive pre-strain on fatigue life

Role of superelasticity in residual stresses
Modeling Residual Stresses
Diamond Specimens
Tension Specimens
Pre-strain Diamond Test Results
Role of Superelasticity in Residual Stresses
Pre-Strain Diamond Geometry

Diamonds were designed to achieve high pre-strains.

Only the extrados location of the diamond was focused to achieve the desired stress/strain state.
Stress Free Diamond
Tensile Pre-Stress State

S, Max. Principal (Abs) (Average-compute)
+1.214e+03
+1.026e+03
+8.381e+02
+6.502e+02
+4.623e+02
+2.744e+02
+8.647e+01
-1.014e+02
-2.893e+02
-4.773e+02
-6.652e+02
-8.532e+02
-1.041e+03

Extrados (Tensile stress)


Step: compress Increment 33: Step Time = 1.000
Primary Var: S, Max. Principal (Abs)
Deformed Var: U Deformation Scale Factor: +1.000e+00
Compressive Residual Stress State

S, Max. Principal \{Abs\} (Average-compute)

- +3.949e+01
- +2.139e+01
- +3.284e+00
- -1.482e+01
- -3.292e+01
- -5.103e+01
- -6.913e+01
- -8.724e+01
- -1.053e+02
- -1.234e+02
- -1.415e+02
- -1.597e+02
- -1.778e+02


Step: deploy
Increment 158: Step Time = 1.000
Primary Var: S, Max. Principal (Abs)
Deformed Var: U Deformation Scale Factor: +1.000e+00
Compressive Residual Stress – FEA Sequence

- Compressive Residual Stress
- Tensile Stress
- Pre-strain
- Crimping
- Deployment

Stress (MPa) vs Strain (%)

1. Max. Principal (Max)
   Average (computed)

-1500
-1000
-500
0
500
1000
1500
-10 -8 -6 -4 -2 0 2 4 6 8 10

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Compressive Residual Stress – Test Sequence

Test : Global Force – Displacement

- Load (N)
- Stress (MPa)
- Displacement (mm)
- Strain (%)

Primary Var: L, Max. Principal (Mag)
Deformed Var: U, Deformation Scale Factor: +1,000x (100)

T10-L2_9a
T10-L4_9b
T10-L6_10a
T10-L8_10b
T10-L10_11a
T10-L12_11b
Compressive Cyclic Stress – FEA Sequence

**Compressive Cyclic Stress**

**Duty Cycle**

**Pre-strain**

**Crimping**

**Deployment**

**Stress (MPa)**

**Strain (%)**

**SMST 2017**

**Shape Memory and Superslastic Technologies Conference and Exposition**

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Compressive Cyclic Stress – Test Sequence

Test : Global Force – Displacement

Load (N)
Displacement (mm)

-12
-8
-4
0
4
8
12

-5 -4 -3 -2 -1 0 1 2 3 4 5

T10-L2_9a
T10-L4_9b
T10-L6_10a
T10-L8_10b
T10-L10_11a
T10-L12_11b

Compressive Cyclic Stress

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Modeling Residual Stresses
- Diamond Specimens
- Tension Specimens

Pre-strain Diamond Test Results

Role of Superelasticity in Residual Stresses
Tension Inclusion FEA

Inclusion Size: 4μm x 4μm x 4μm
Mesh Size: 1μm x 1μm x 1μm
Wire diameter: 0.22 mm
Starting State

Void

Inclusion Attached
Stress State – Initial

**Void**

0 MPa

**Inclusion Attached**

0 MPa
Stress State – Pull 10% Global Strain

Void

1567 MPa; SIF= 1.27

Inclusion Attached

1757 MPa; SIF= 1.41
Stress State – Released

**Void**
-720 MPa

**Inclusion Attached**
-710 MPa
Effect of Residual Stresses on Upper Plateau Stress – Without Pre-straining (6% global strain)

**Void**
1063 MPa

**Inclusion Attached**
790 MPa
Effect of Residual Stresses on Upper Plateau Stress – With 10% Pre-straining (6% global strain)

Void
741 MPa
30% drop

Inclusion Attached
613 MPa
22% drop

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Modeling Residual Stresses

Pre-strain Diamond Test Results

Test Methodology
Baseline
Tensile Pre-strain
Compressive Pre-strain

Role of Superelasticity in Residual Stresses
Extrados Stress States – Naming Convention

Pre-Stress/Strain – PS

Residual Stress/Strain – RS (Depends on Pre-Stress history)

Cyclic Stress/Strain – CS

<table>
<thead>
<tr>
<th>Combination</th>
<th>Pre-Stress State (PS)</th>
<th>Residual Stress State (RS)</th>
<th>Cyclic Stress State (CS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>(+)</td>
<td>(-)</td>
<td>(-)</td>
</tr>
<tr>
<td>B</td>
<td>(-)</td>
<td>(+)</td>
<td>(-)</td>
</tr>
<tr>
<td>C</td>
<td>(+)</td>
<td>(-)</td>
<td>(+)</td>
</tr>
<tr>
<td>D</td>
<td>(-)</td>
<td>(+)</td>
<td>(+)</td>
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</tbody>
</table>

(+) Tensile  
(-) Compressive

Inverse Sign
Fatigue life improves when pre-stress and cyclic stress are of same polarity.

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</tr>
<tr>
<td>D</td>
<td>(-)</td>
<td>(+)</td>
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</tr>
</tbody>
</table>

(+): Tensile
(-): Compressive

Inverse Sign
## Global Force Displacement – Test

<table>
<thead>
<tr>
<th></th>
<th>PS+ (Crimp to achieve tensile stress at extraod and compressive residual stress)</th>
<th>PS- (Crimp to achieve compressive stress at extraod and tensile residual stress)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS-</td>
<td><img src="image" alt="Graph A" /> (Cycle diamond partially stretched, to achieve compressive cyclic stress on extraod)</td>
<td><img src="image" alt="Graph B" /> (Cycle diamond partially stretched, to achieve compressive cyclic stress on extraod)</td>
</tr>
<tr>
<td>CS+</td>
<td><img src="image" alt="Graph C" /> (Cycle diamond partially crimped, to achieve tensile cyclic stress on extraod)</td>
<td><img src="image" alt="Graph D" /> (Cycle diamond partially crimped, to achieve tensile cyclic stress on extraod)</td>
</tr>
</tbody>
</table>

**Graphs:**

- **Graph A:** Shows the load vs. displacement for PS+ configuration with different markers indicating varying conditions or samples.
- **Graph B:** Similar setup to A but for PS- configuration.
- **Graph C:** Displays the load vs. displacement for CS+ condition.
- **Graph D:** Similar setup to C but for CS- configuration.
Pre-Stress Diamond Test Conditions

Material: SE508-ELI
Sample size: 6 Diamonds (or 12 ‘V’ s at each condition)
Test Temperature: 37°C

Pre-strain (Tensile or compressive) : 9%
Mean strain: 3.50%
Starting strain amplitude: 0.75%
Run out: 1 million cycles ;
Increase cyclic displacements until specimens fracture
Modeling Residual Stresses

**Pre-strain Diamond Test Results**

- Test Methodology
- **Baseline**
- Tensile Pre-strain
- Compressive Pre-strain

**Role of Superelasticity in Residual Stresses**
Baseline Test Force Displacement
Baseline Test Results

Mean strain: 3.50%
Run out: 1 million cycles
Sample size: 12 at each condition

<table>
<thead>
<tr>
<th>Strain Amplitude (%)</th>
<th>Baseline (PS0, CS+)</th>
<th>Combination A (PS+, RS-, CS-)</th>
<th>Combination B (PS-, RS+, CS-)</th>
<th>Combination C (PS+, RS-, CS+)</th>
<th>Combination D (PS-, RS+, CS+)</th>
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<tr>
<td>0.75</td>
<td>Run Out</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.30</td>
<td>Run Out</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.88</td>
<td>Run Out</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.24</td>
<td>Fracture (2)</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>2.76</td>
<td>Fracture (5)</td>
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</tr>
<tr>
<td>2.90</td>
<td>Fracture (3)</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>3.03</td>
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<td>3.16</td>
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Modeling Residual Stresses

Pre-strain Diamond Test Results

Test Methodology
Baseline
Tensile Pre-strain
Compressive Pre-strain

Role of Superelasticity in Residual Stresses
Global Force Displacement – Test

PS+  
Crimp to achieve tensile stress at extradoses, and compressive residual stress

CS+  
Cycle diamond partially stretched, to achieve compressive cyclic stress on intradoses

CS+  
Cycle diamond partially clipped, to achieve tensile cyclic stress on extradoses

Load (N) vs. Displacement (mm)
### Tensile Pre-Strain Results

**Pre-strain:** (+) 9.00%

**Mean strain:** 3.50%

**Run out:** 1 million cycles ; **Sample size:** 12 at each condition

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<tr>
<td>1.88</td>
<td>Run Out</td>
<td>Fracture (4)</td>
<td>Run Out</td>
<td>Run Out</td>
<td>Run Out</td>
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<td>2.24</td>
<td>Fracture (2)</td>
<td>Fracture (1)</td>
<td>Run Out</td>
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<td>Fracture (2)</td>
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**Fracture Initiation:**
- Intrados
- Extrados
Modeling Residual Stresses

Pre-strain Diamond Test Results

- Test Methodology
- Baseline
- Tensile Pre-strain
  *Compressive Pre-strain*

Role of Superelasticity in Residual Stresses
Global Force Displacement – Test

Cycle diamond partially stretched, to achieve compressive cyclic stress on extrados

Cycle diamond partially clipped, to achieve tensile cyclic stress on extrados

PS-

Crimp to achieve compressive stress at extrados, and tensile residual stress

(A)

(B)

(D)
## Compressive Pre-Strain Results

Pre-strain: \((-\) 9.00\%

Mean strain: 3.50\%

Run out: 1 million cycles ; Sample size: 12 at each condition

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Fracture Initiation: Intrados
Fracture Initiation: Extrados

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Survival Plot – Diamond Surrogates

Mean Strain: 3.5%
Pre-strain: 9%
Modeling Residual Stresses
Pre-strain Diamond Test Results
Role of Superelasticity in Residual Stresses
Residual Stress State – Inclusion Attached (Steel vs. Nitinol)

Inclusion Attached

Steel 316L
-450 MPa

Inclusion Attached

Nitinol
-710 MPa
Residual Stress State – Void (Steel vs. Nitinol)

Steel 316L
-420 MPa

Nitinol
-720 MPa
Summary

Residual stresses through pre-straining can increase or decrease the fatigue life depending on the nature of pre-strain and cyclic stress state.

Fatigue life improves when the pre-stress and cyclic stress are of the same polarity (i.e., tensile or compressive).

The effect of residual stresses is more pronounced in Nitinol compared to a traditional metal.
bit.ly/smst17ndc

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