TIIMS

TEXAS INSTITUTE FOR INTELLIGENT BIO-NANO MATERIALS AND STRUCTURES FOR AEROSPACE VEHICLES

A NASA University Research, Engineering and Technology Institute (URETI)

Characterization of the Nonlinear Rate Dependent Response of Shape Memory Polymers

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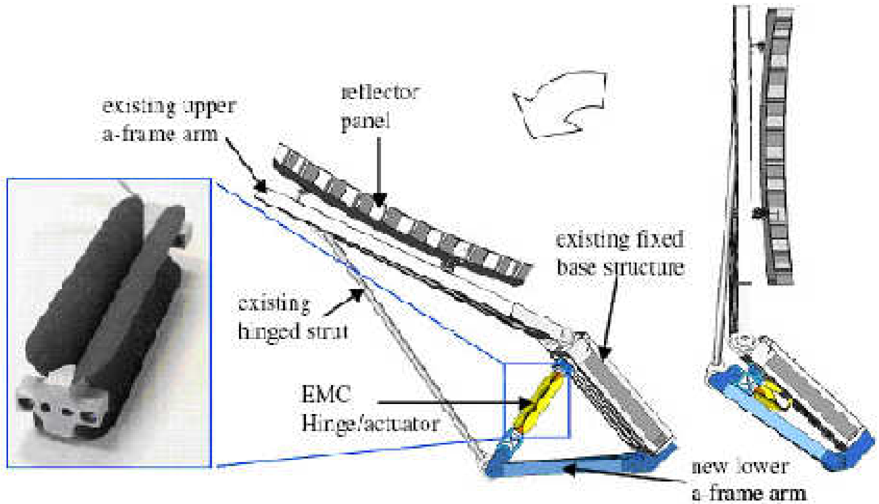
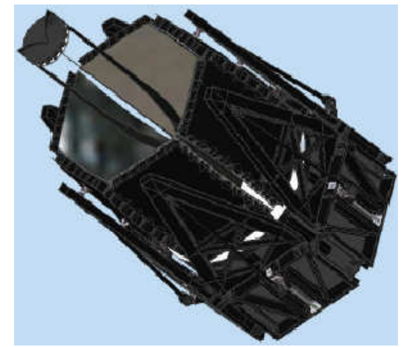
Motivation

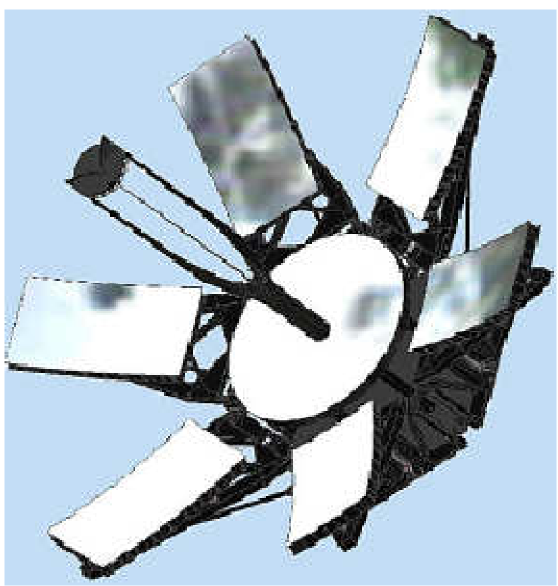
- **Shape Memory Polymer (SMP) Advantages**
  - **Ability to recover strains up to 400%**
  - **Lightweight and Inexpensive (Compared to Shape Memory Alloys)**

- **Applications**
  - **Deployable Space Structures**
  - **Flexible Biodegradable Applications (i.e. sutures)**

Deployable Space Structure







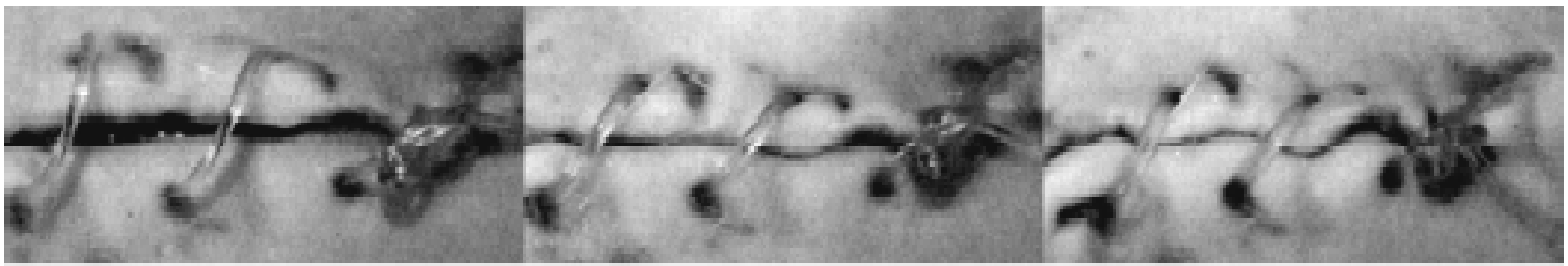
LIDAR 3-meter-class deployable reflector system

Advantages of EMC hinges comparing with mechanical actuators:

- **Eliminate the need for mechanical latches and the post-deployed micro-dynamic instabilities.**
- **Provide a low shock and controlled deployment.**
- **Lightweight, simple, and low coefficient of thermal expansion.**

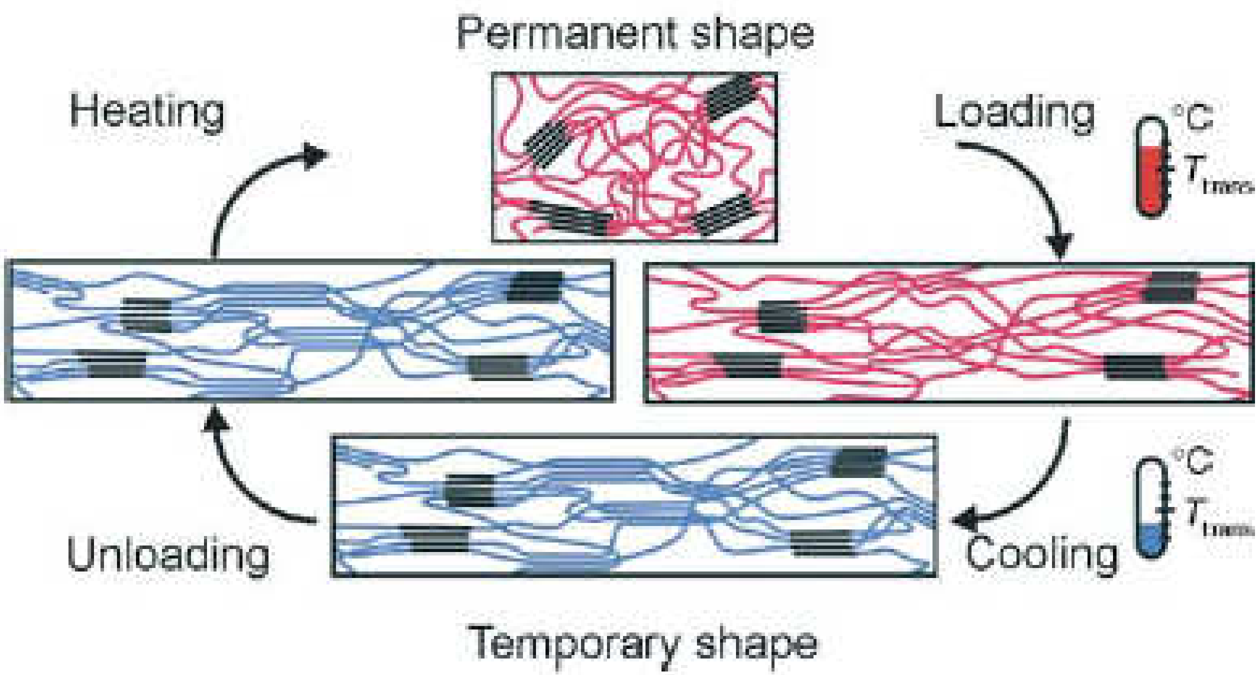
Flexible Biodegradable Sutures

The suture, in its temporary shape at the room temperature, is placed loosely on the wound. Upon being heated to the body temperature, the suture shrinks to its permanent shape. After the wound heals, the suture is eventually absorbed.



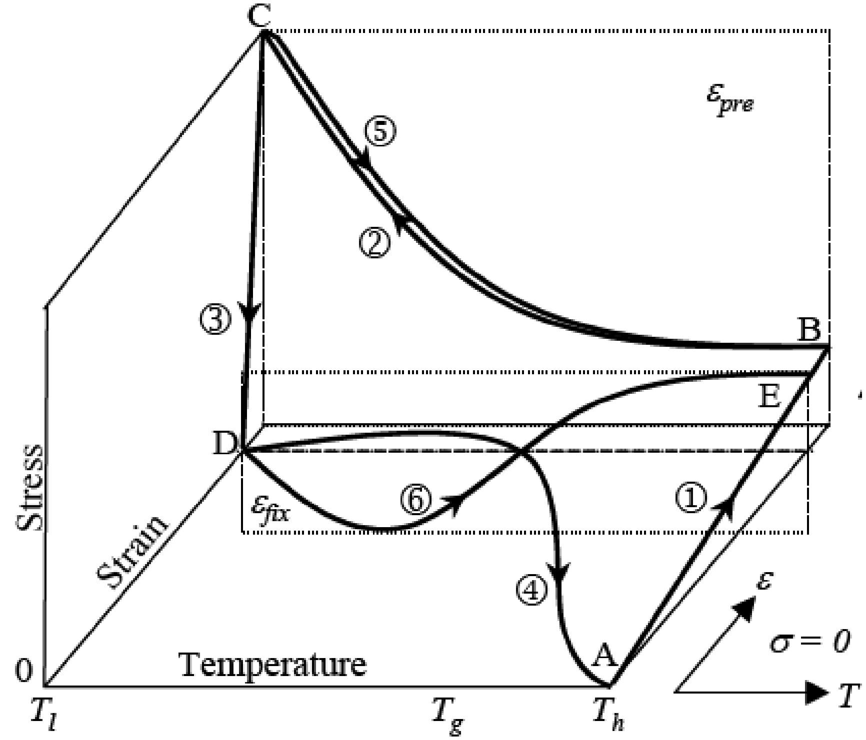
20℃ 37℃ 41℃

Shape Memory Effect



Schematic demonstration of the molecular mechanism of the thermally induced shape-memory effect for a multi-block copolymer.

Thermomechanical Loading



A typical shape memory thermal/loading cycle:

1. Loading at high temperature.
2. Cooling at fixed strain.
3. Unloading at low temperature.
4. Heating at zero stress.

Path 5 corresponds to heating at fixed strain before unloading, and path 6 to Heating at fixed strain after unloading.

Research Objectives

- **Constitutive Model**
  - **Nonlinear (Shape Recovery vs. Time)**
  - **Rate Dependent (i.e. Heating, Loading Rate)**
  - **Account for Large Deformations (Applied Strain > 10%)**

- **Experimental Focus**
  - **Calibrate Model**
  - **Verify Simulation Results**

Constitutive Modeling of SMPs

- Bhattacharyya and Tobushi, 2000. Rheological approaches with no strain storage and release mechanisms.
- Rao, 2002. Dividing the SMP into four parts of different molecular structures and crystallization, and deriving the overall constitutive equation using a mixture theory.
- Liu and Gall, 2005. A 1-D small-strain model based on strain storage and release mechanisms at the molecular level. Pertinent only to the particular thermal/loading paths of their experiments.
- Present theory. A 3-D thermoelastic constitutive model for large deformation of SMPs under arbitrary thermal/loading paths.

Constitutive Equations

State variables:

- Deformation $\mathbf{x}(\mathbf{X}, t)$,
- Deformation gradient $\mathbf{F}(\mathbf{X}, t)$,
- Piola-Kirchhoff $\mathbf{S}(\mathbf{X}, t)$,
- Temperature $\theta(\mathbf{X}, t)$.

Two constitutive functions, $\hat{\mathbf{F}}_a(\mathbf{S}, \theta)$ and $\hat{\mathbf{F}}_f(\mathbf{S}, \theta)$, are taken for the active phase and frozen phase, respectively.

Need to stipulate how the constitutive functions switch when the material undergoes the phase transition.

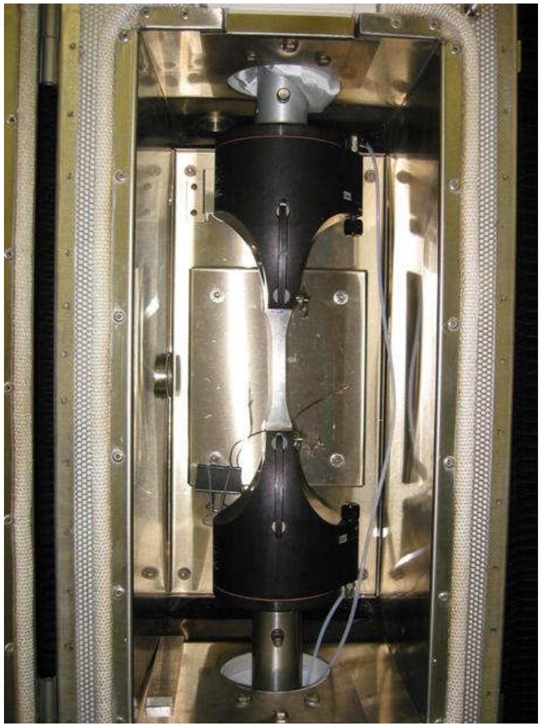
Constitutive Assumptions

1. The deformation at a material point is preserved (stored) when it undergoes transition from the active phase to frozen phase. It is assumed that if the temperature and the stress are continuous in time, then the deformation gradient must be continuous in time, despite the change of the constitutive function from $\hat{\mathbf{F}}_a$ to $\hat{\mathbf{F}}_f$ when the interface passes through the material point.

2. The stored deformation at a frozen material point is fully recovered when the interface passes through it again during subsequent heating.

Experimental Setup

- **Electromechanical, Screw-Driven Test Frame**
  - **MTS Alliance RT-1**
- **MTS 1000 N Load Cell**
- **MTS 2000 N Pneumatic Grips**
- **Thermcraft Oven with Temperature Controller**
- **Optical Strain Measurement**

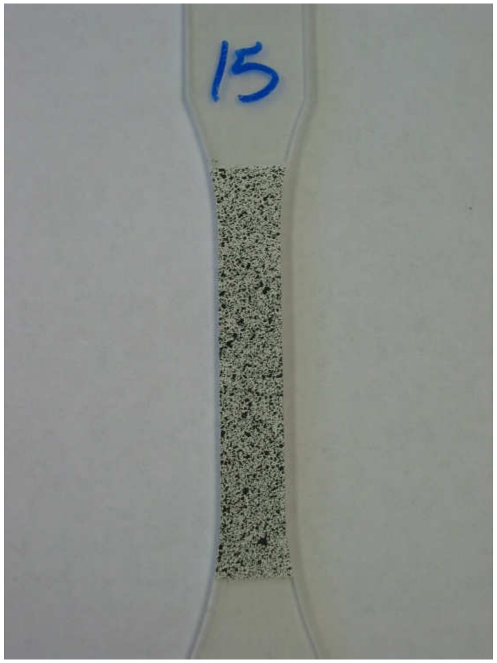


Strain Measurement

- **Visual Imaging Correlation (VIC) System**
- **Two Camera Setup**
- **Tracks “Speckled” Pattern**
  - **Large Travel Capability**
- **Provides Full-Field Strain Measurements**

Specimen Preparation

- **Provided by Cornerstone Research Group, Inc.**
- **Dogbone Specimens (ASTM D638)**
  - **Cut via Water-jet**
- **Gauge Length – 57 mm**
- **Gauge Width – 12.7 mm**
- **High-Contrast Speckled Pattern Painted on Surface**

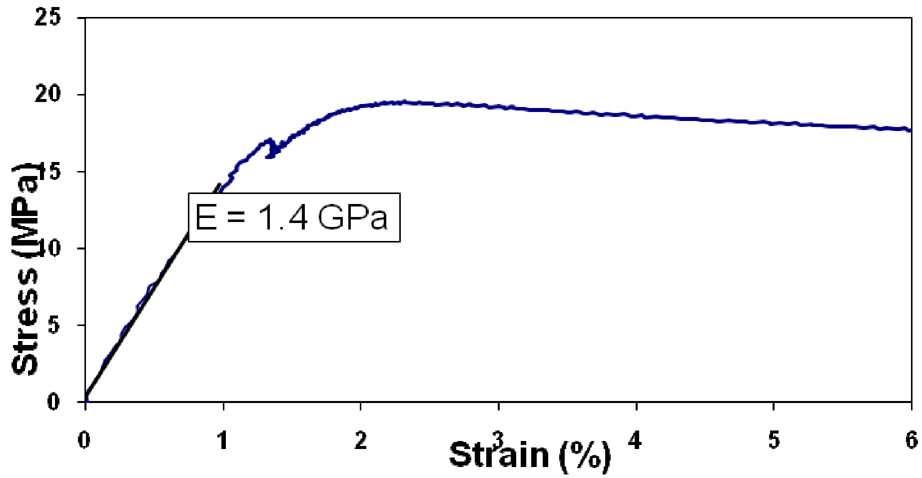


Material Properties

- **Glass Transition Temperature – 58℃**
  - **Measured via ThermoMechanical Analyzer (TMA)**

- **Coefficient of Thermal Expansion – 8.6E-07/℃**

- **Young's Modulus**
  - **Glass Phase: 1.4 GPa**
  - **Rubber Phase: N/A**



- **Tensile Strength (Glass Phase) ~ 20 MPa**

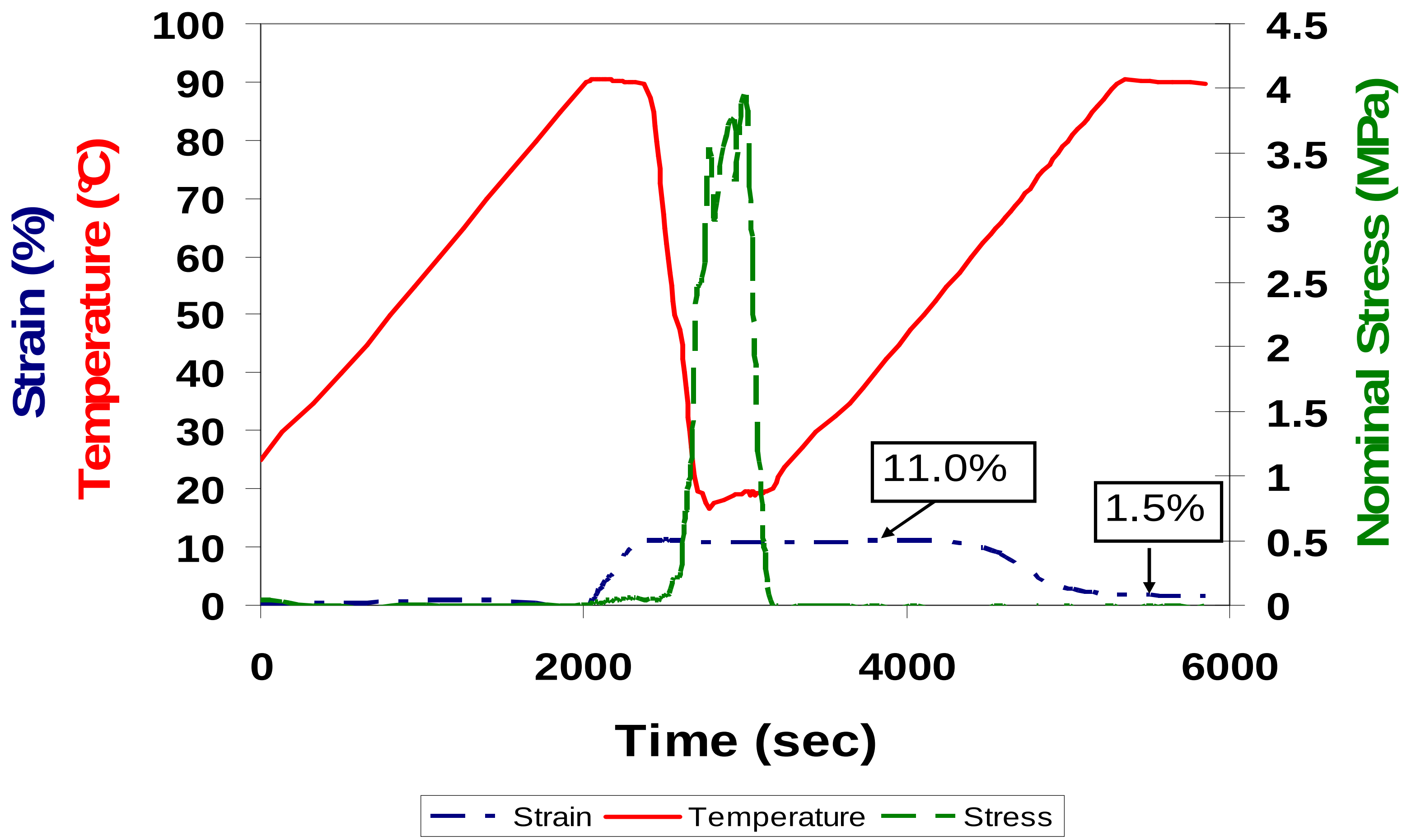
Test Matrix

Test Case	Test Number	Prestrain	Recovery Temperature	Recovery Stress (MPa)	Recovery Strain Rate
Constant Stress Recovery	A.1.1.1	$\varepsilon_0 = 10\%$	T = Tg + 30 (~90°C)	$\sigma_1 = 0$	Output
	A.1.1.2			$\sigma_2 = 1$	
	A.1.1.3			$\sigma_3 = 2$	
	A.2.1.1	$\varepsilon_0 = 25\%$	T = Tg + 30 (~90°C)	$\sigma_1 = 0$	
	A.2.1.2			$\sigma_2 = 1$	
	A.2.1.3			$\sigma_3 = 2$	
	A.3.1.1	$\varepsilon_0 = 50\%$	T = Tg + 30 (~90°C)	$\sigma_1 = 0$	
	A.3.1.2			$\sigma_2 = 1$	
	A.3.1.3			$\sigma_3 = 2$	
	A.4.1.1	$\varepsilon_0 = 100\%$	T = Tg + 30 (~90°C)	$\sigma_1 = 0$	
	A.4.1.2			$\sigma_2 = 1$	
	A.4.1.3			$\sigma_3 = 2$	
Constant Strain Rate Recovery	B.1.1.1	$\varepsilon_0 = 10\%$	T = Tg + 30 (~90°C)	Output	$\dot{\varepsilon}_1 = 10^{-2}$
	B.1.1.2				$\dot{\varepsilon}_2 = 10^{-3}$
	B.2.1.1	$\varepsilon_0 = 25\%$	T = Tg + 30 (~90°C)		$\dot{\varepsilon}_1 = 10^{-2}$
	B.2.1.2				$\dot{\varepsilon}_2 = 10^{-3}$
	B.3.1.1	$\varepsilon_0 = 50\%$	T = Tg + 30 (~90°C)		$\dot{\varepsilon}_1 = 10^{-2}$
	B.3.1.2				$\dot{\varepsilon}_2 = 10^{-3}$
	B.4.1.1	$\varepsilon_0 = 100\%$	T = Tg + 30 (~90°C)		$\dot{\varepsilon}_1 = 10^{-2}$
	B.4.1.2				$\dot{\varepsilon}_2 = 10^{-3}$

Testing Parameters

1. **Initial State**
   - Room Temperature ($T < T_g$)
   - Stress-Free and Strain-Free
2. **Heat Material to 90°C ($T > T_g$) at 2°C/min**
   - Maintain Zero-Stress (Thermal Expansion Permitted)
3. **Strain Material to Predetermined Level**
   - Tests Included Strain Levels of 10, 25, 50, and 100%
4. **Cool Material to Room Temperature ($T < T_g$)**
   - Maintain Deformed Shape (Strain = Constant)
   - Thermal Stress Induced
5. **Unload Material to Zero-Stress**
6. **Heat Material to 90°C at 2°C/min**
   - Shape Recovery Occurs

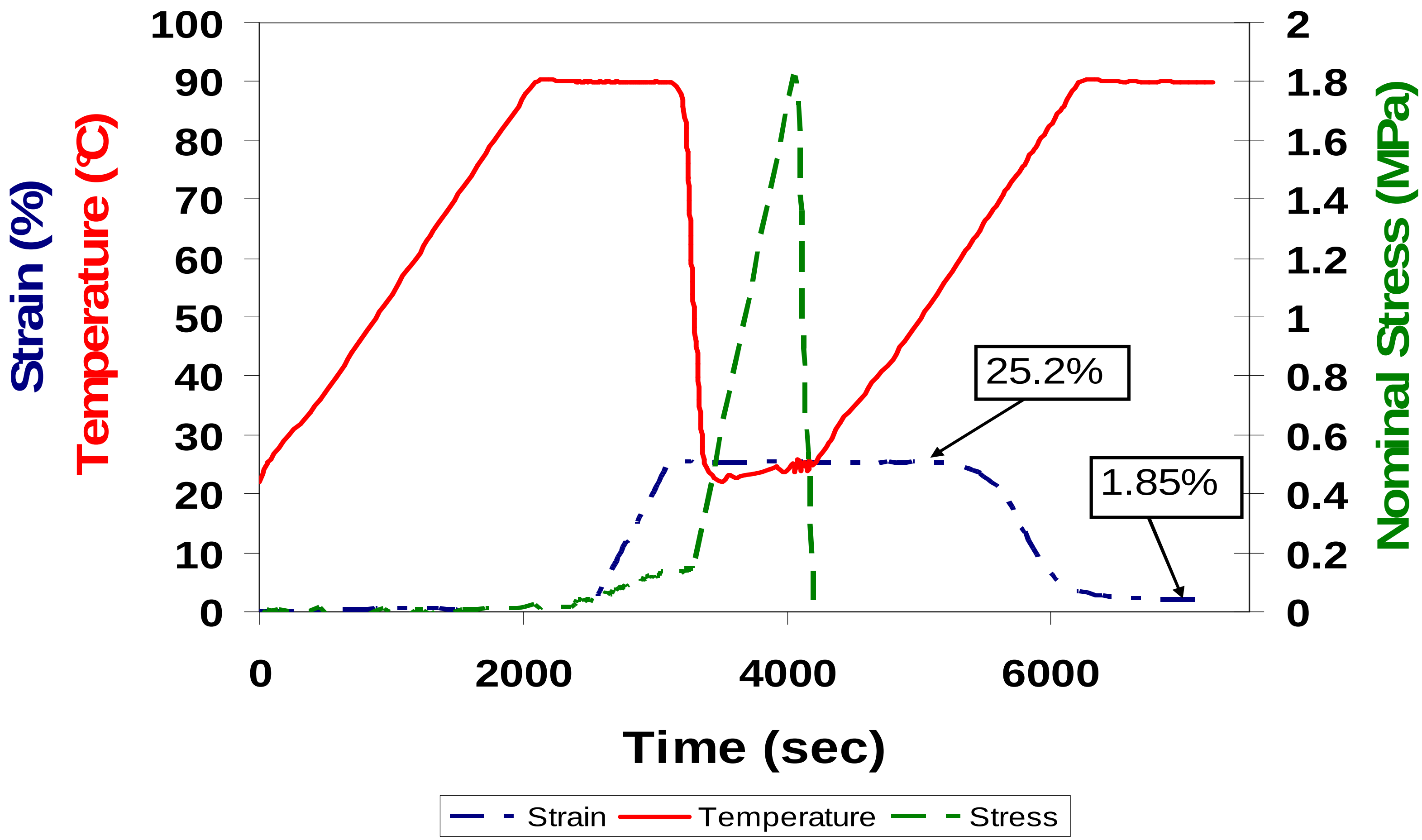
Results



11% Applied Strain

1.5% Unrecoverable Strain

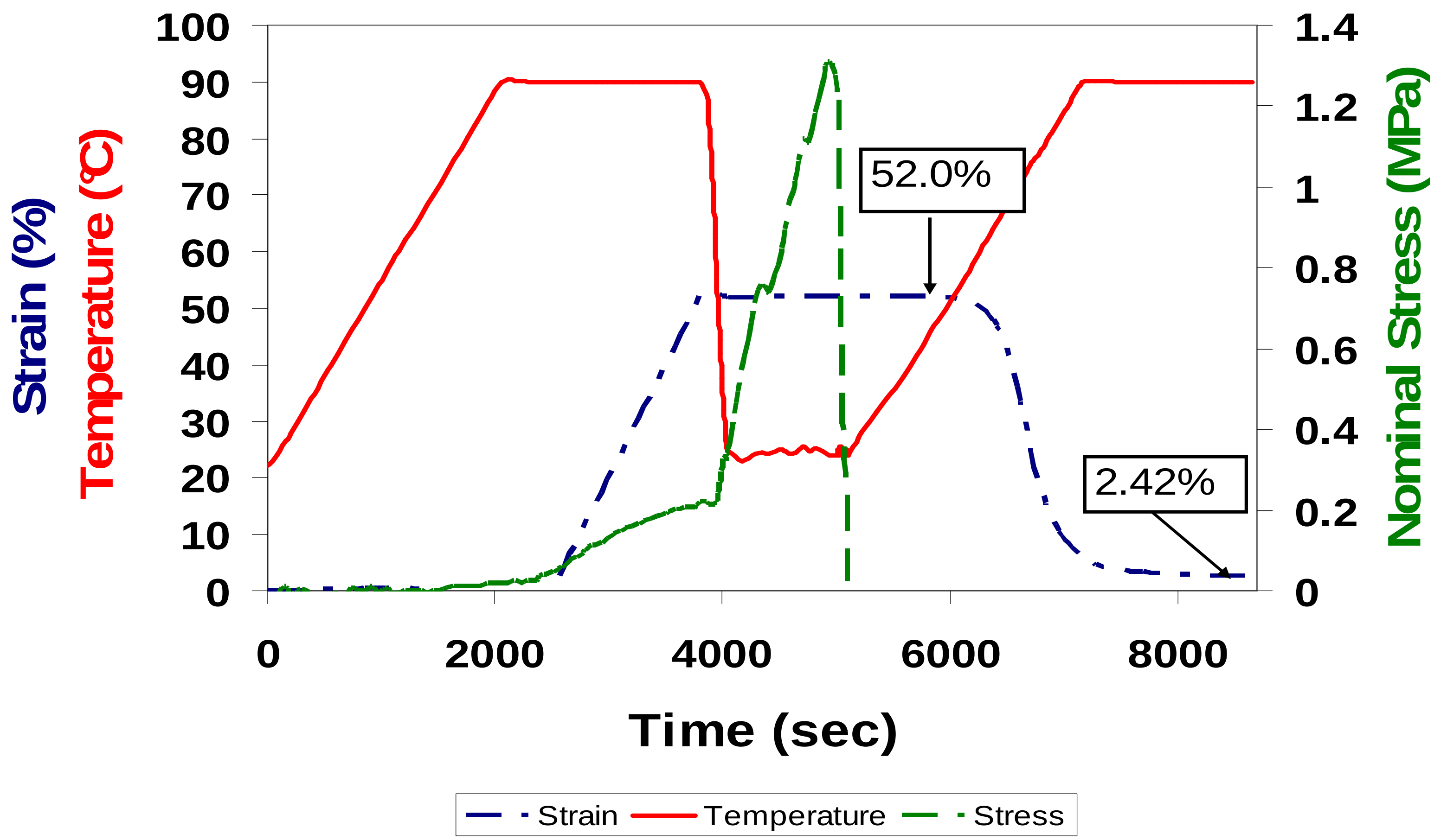
Results



25% Applied Strain

1.9% Unrecoverable Strain

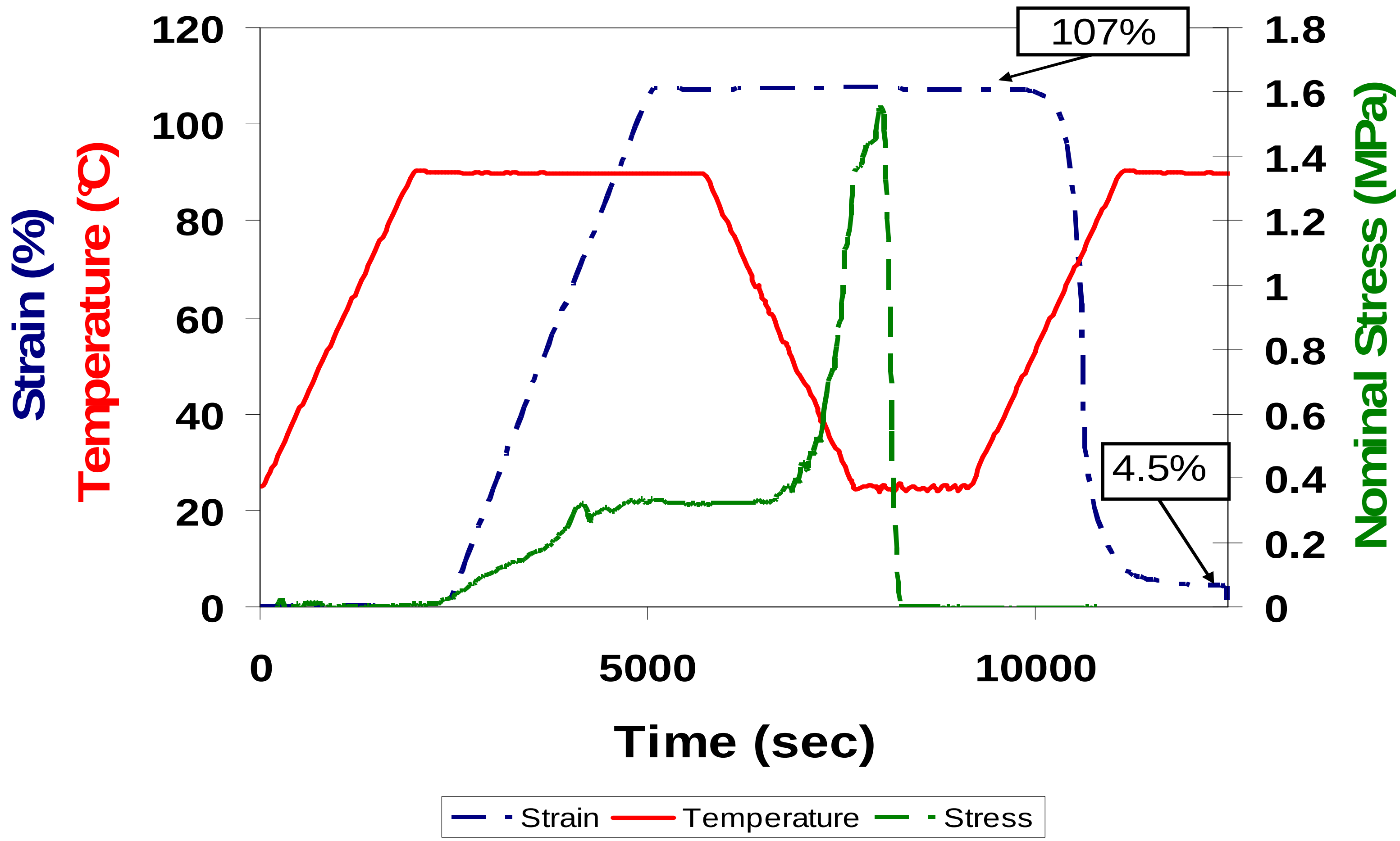
Results, cont'd.



52% Applied Strain

2.4% Unrecoverable Strain

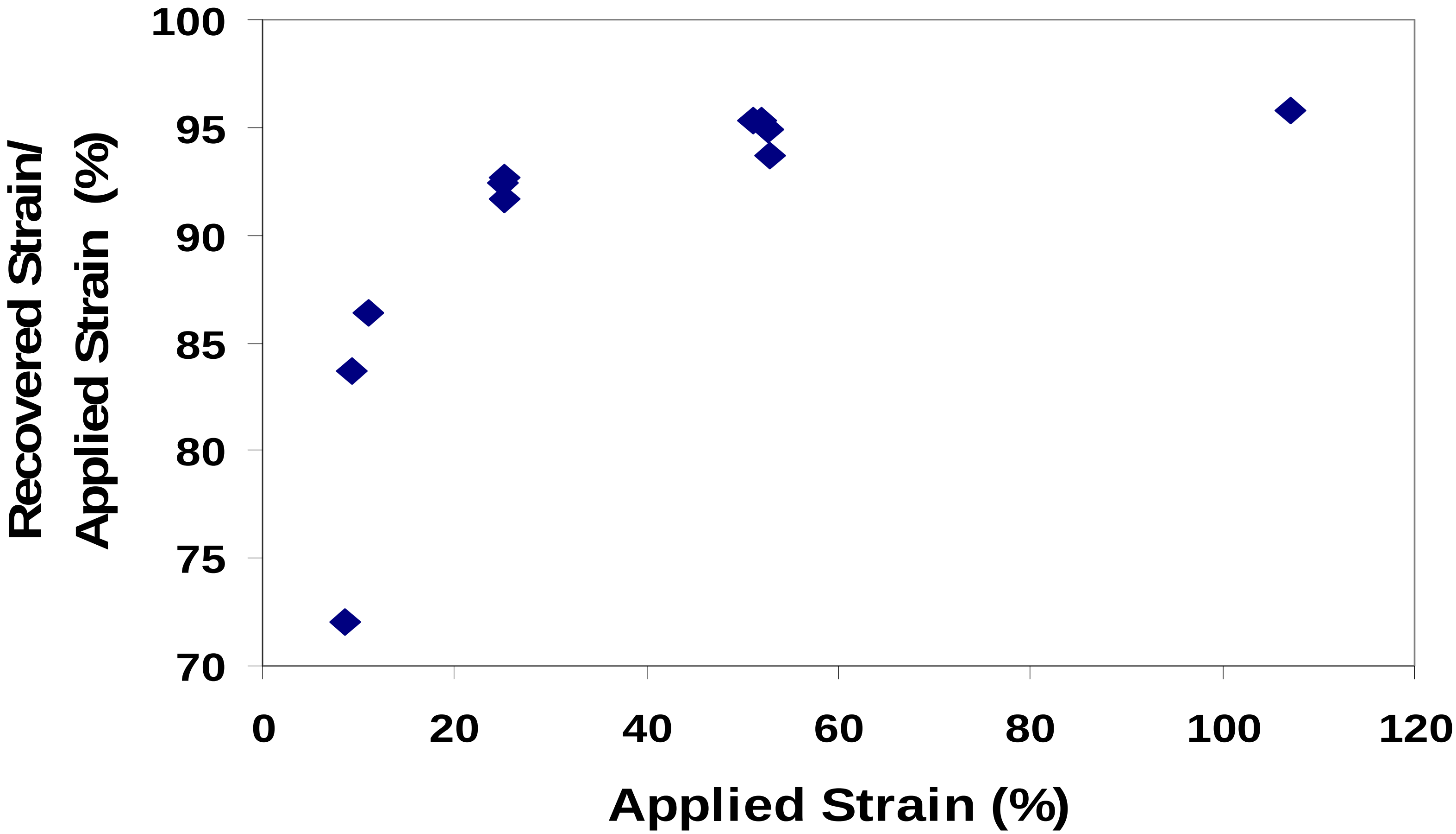
Results, cont'd.



107% Applied Strain

4.5% Unrecoverable Strain

Results, cont'd.



Percentage of Unrecoverable Strain/Applied Strain Approaches Asymptotic Value

Conclusions

- **Successful 10, 25, 50, and 100% Experimental Tests Performed**
- **Nonlinear Shape Recovery Observed**
  - **Majority Occurring Shortly After T Exceeds T_g**
- **Important Application Consideration:**
  - **Percentage of Unrecoverable Strain/Applied Strain**
- **Unique Ability to Perform Complex Thermomechanical Characterization for Large Deformations**

Future Work

- **Continue Zero-Stress Recovery Tests**
  - **Greater than 100% Strain**
- **Investigate Rate Dependence**
  - **Heating/Cooling Rate**
  - **Loading Rate**
- **Perform Tests with Recovery Stress > 0**
- **Investigate Effects of Final Heating/Cooling Temperatures**
- **Obtain Additional Parameters as Demanded by Model Development**

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