Iron Based Transforming Single Crystals

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Presentation Outline

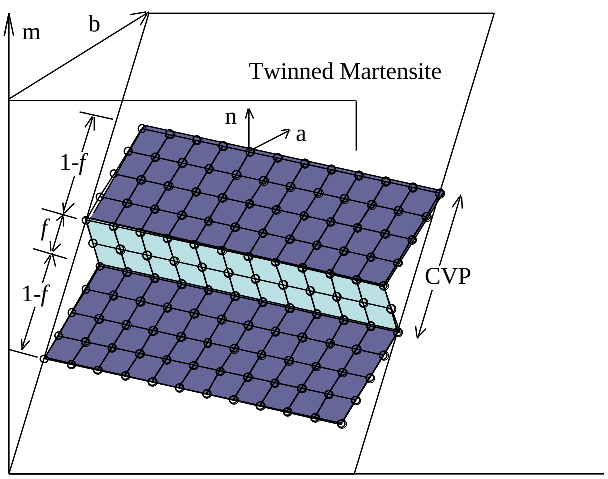
- Relevancy
- Background
- Theoretical Calculations of Transformation Strains
- Shape Memory Behavior in Tension and Compression
- Temperature Cycling under Stress
- Potential Applications

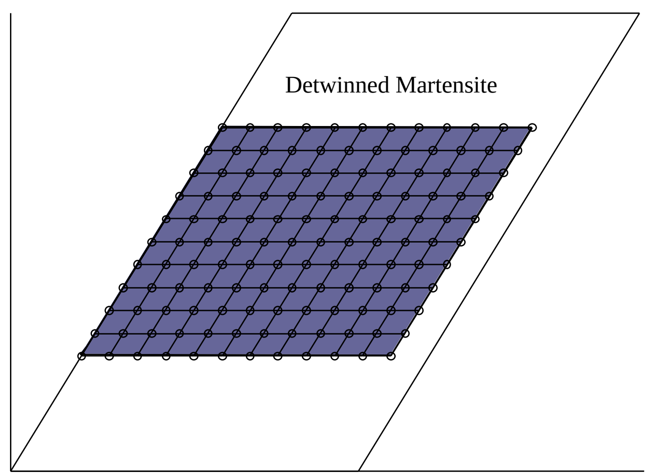
Background

- The objective is to develop iron based transforming (shape memory) materials with high strength combined with high resistance to slip and fatigue.
- Previous iron based transforming materials (Fe-Mn-Si) do not possess high strength and exhibit small recoverability of strains. The NiTi materials have the recoverability but lower strength. The FeNiCoTi demonstrate enormous potential when both strength and recoverability are considered.
- We are systematically measuring transformation stresses and strains, electrical resistance to develop optimum FeNiCoTi compositions and aging treatments. We calculate the transformation behavior based on lattice parameters.

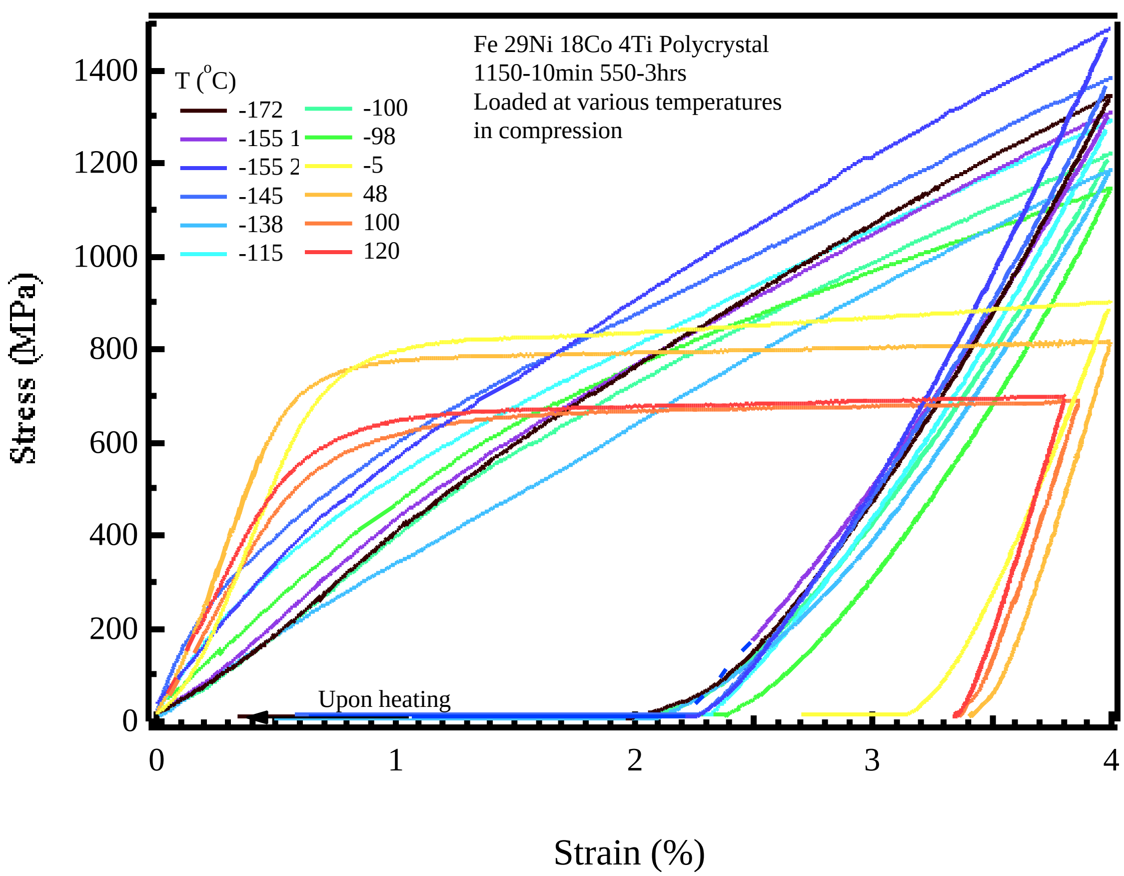
Recent Developments

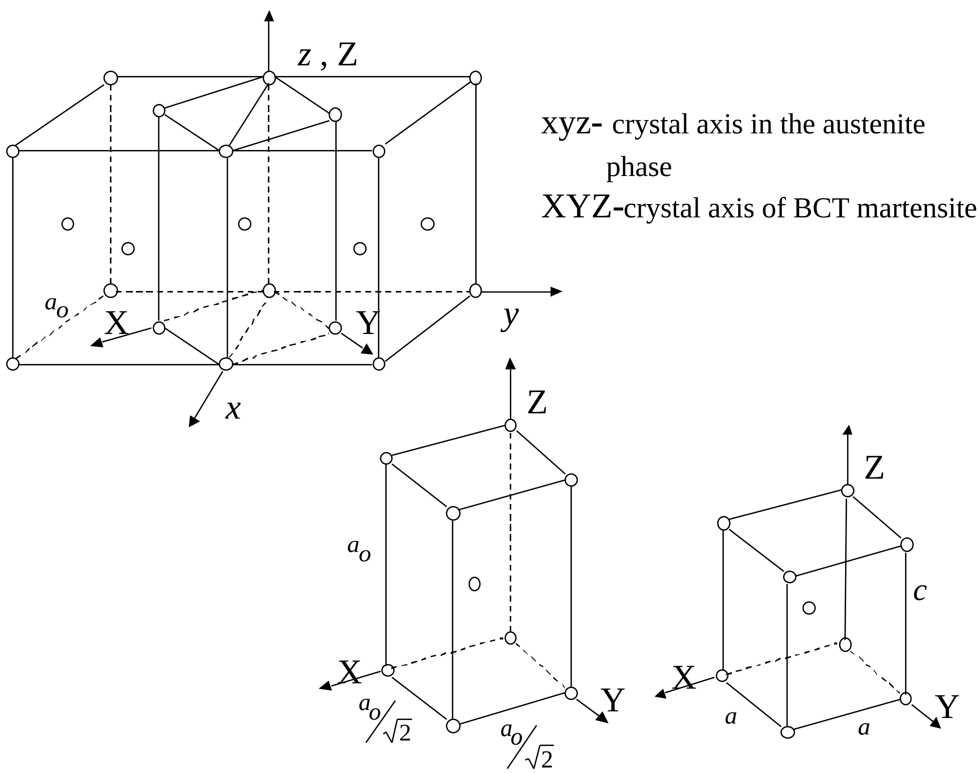
- We demonstrate theoretically that these alloys can exhibit high transformation strains and high stresses.
- We have discovered Fe SMA compositions which produce high strength and good recoverability levels which have not been attained before. By varying the titanium content, we intend to minimize slip and enhance transformation characteristics.





Stress-strain Response under Compression




z , Z
xyz- crystal axis in the austenite phase
XYZ-crystal axis of BCT martensite
a_o
X
Y
y
x
Z
a_o
X
Y
$a_o/\sqrt{2}$
$a_o/\sqrt{2}$
Z
c
X
Y
a
a

Three Lattice Correspondences of Martensite

	Variant 1	Variant 2	Variant 3
$[100]_T$	$\frac{1}{2}[110]_C$	$\frac{1}{2}[011]_C$	$\frac{1}{2}[101]_C$
$[010]_T$	$\frac{1}{2}[\bar{1}10]_C$	$\frac{1}{2}[0\bar{1}1]_C$	$\frac{1}{2}[\bar{1}01]_C$
$[001]_T$	$[001]_C$	$[100]_C$	$[010]_C$

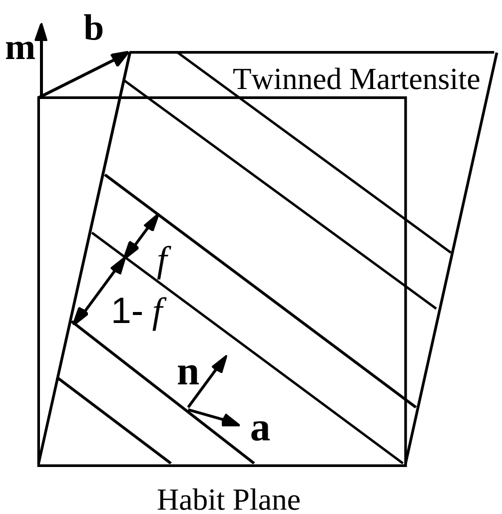
$$\mathbf{F}_1 = \begin{bmatrix} \frac{a}{a_0} & \frac{a}{a_0} & 0 \\ -\frac{a}{a_0} & \frac{a}{a_0} & 0 \\ 0 & 0 & \frac{c}{a_0} \end{bmatrix} = \text{Deformation Gradient}$$

$$\mathbf{U}_1 = \begin{bmatrix} \eta_1 & 0 & 0 \\ 0 & \eta_1 & 0 \\ 0 & 0 & \eta_2 \end{bmatrix}, \mathbf{U}_2 = \begin{bmatrix} \eta_2 & 0 & 0 \\ 0 & \eta_1 & 0 \\ 0 & 0 & \eta_1 \end{bmatrix}, \mathbf{U}_3 = \begin{bmatrix} \eta_1 & 0 & 0 \\ 0 & \eta_2 & 0 \\ 0 & 0 & \eta_1 \end{bmatrix}$$

= symmetric part of F

$$\eta_1 = \frac{\sqrt{2}a}{a_0}, \eta_2 = \frac{c}{a_0}$$

Schematic of Variants, Habit Planes, Twins, CVPs



m= habit plane normal

b=transformation shear of martensite

f= volume fraction of twins within the martensite

n=twin plane normal

a= twinning shear

$a_o = 3.61A, a = 2.8A, c = 3.01A$

m= {0.744,0.2189,-0.6552}

b= {0.1241,-0.2577,0}

Deformation Gradient Associated with CVP Formation

$$\mathbf{F}_M = \mathbf{R}_h[f\,\mathbf{R}_{ij}\mathbf{U}_j + (1 - f)\mathbf{U}_i)$$

$\mathbf{R}_h$ = relative rotation between the twinned martensite and the parent phase

$\mathbf{R}_{ij}$ = relative rotation between the two variants

Strain associated with CVP Formation

$$\varepsilon = \frac{1}{2}(\mathbf{F}_M^T \quad \mathbf{F}_M - \mathbf{I}) = \frac{1}{2}[\mathbf{b} \quad \mathbf{m} + \mathbf{m} \quad \mathbf{b} + (\mathbf{b} \;\; \mathbf{b})\mathbf{m} \quad \mathbf{m}]$$

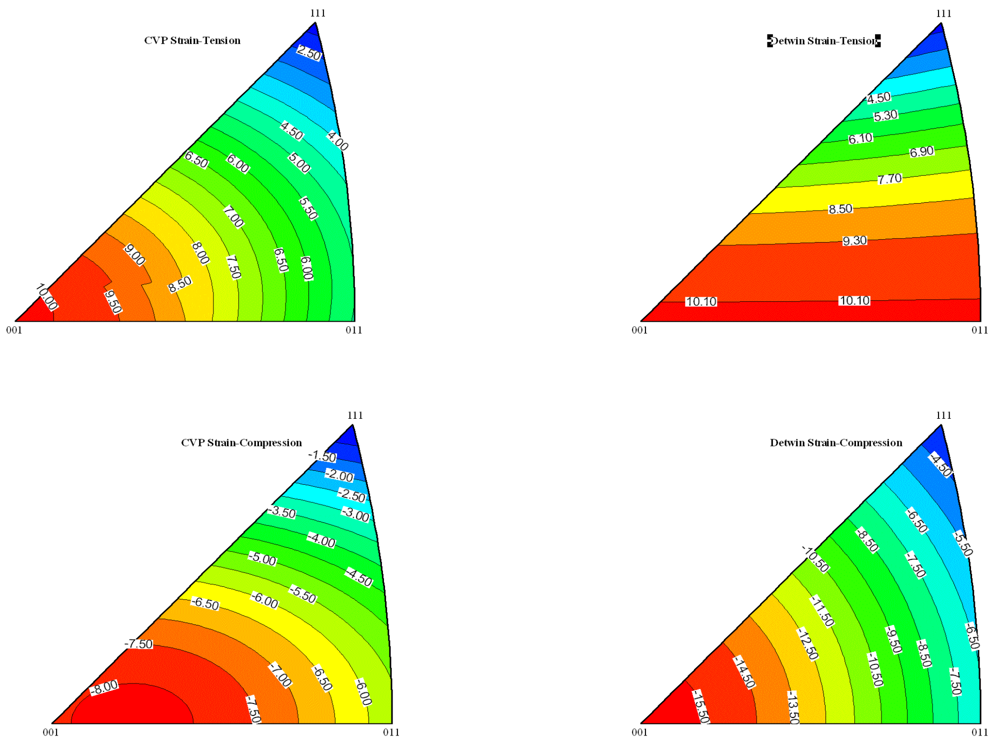
Deformation Gradient Associated with Detwinning

$$\mathbf{F}_M^{dt} = \mathbf{R}_h\mathbf{R}_{ij}\mathbf{U}_j = \mathbf{R}_h \;(\mathbf{U}_i + \mathbf{a} \quad \mathbf{n})$$

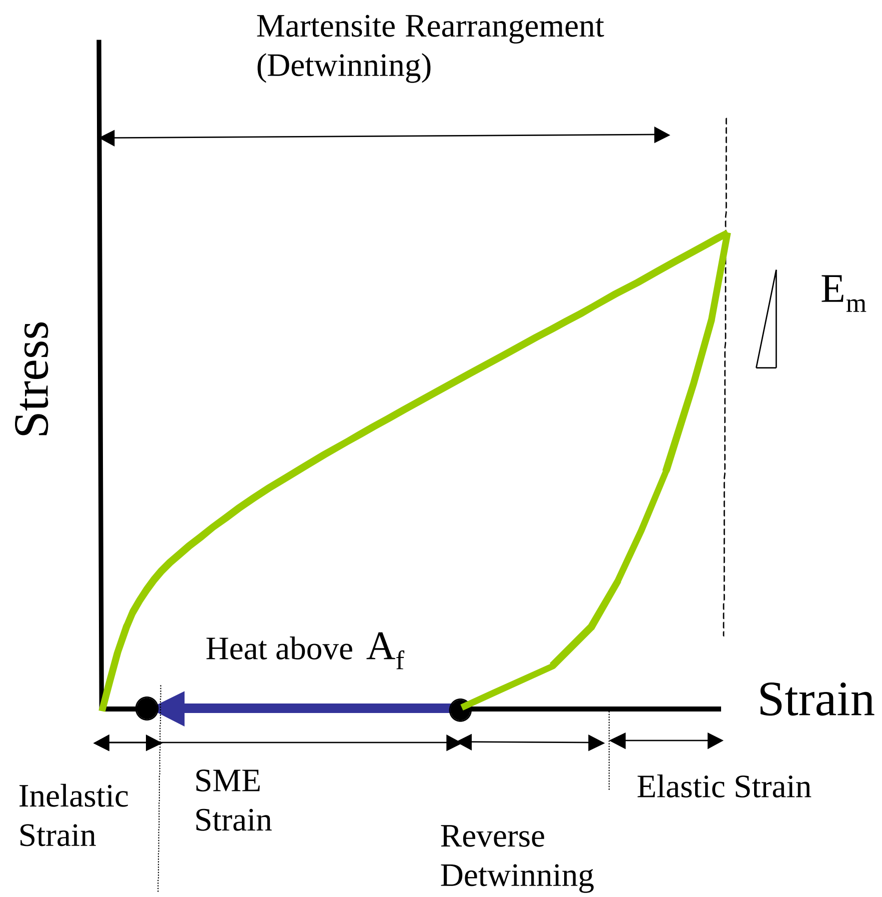
Additional strain associated with Detwinning

$$\varepsilon = \frac{1}{2}(\mathbf{F}_M^{dtT} \quad \mathbf{F}_M^{dt} - \mathbf{I}) = \frac{1}{2}[\mathbf{b} \quad \mathbf{m} + \mathbf{m} \quad \mathbf{b} + (\mathbf{b} \;\; \mathbf{b})\mathbf{m} \quad \mathbf{m}]$$

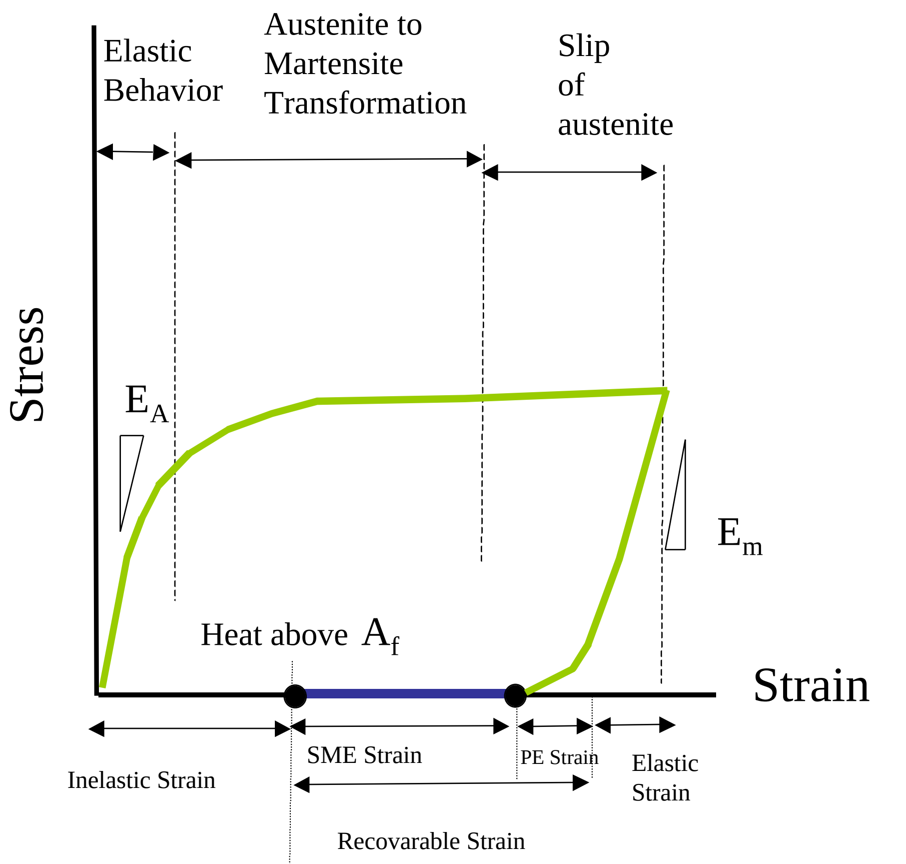
Theoretical Calculations of CVP and Detwinning Strains



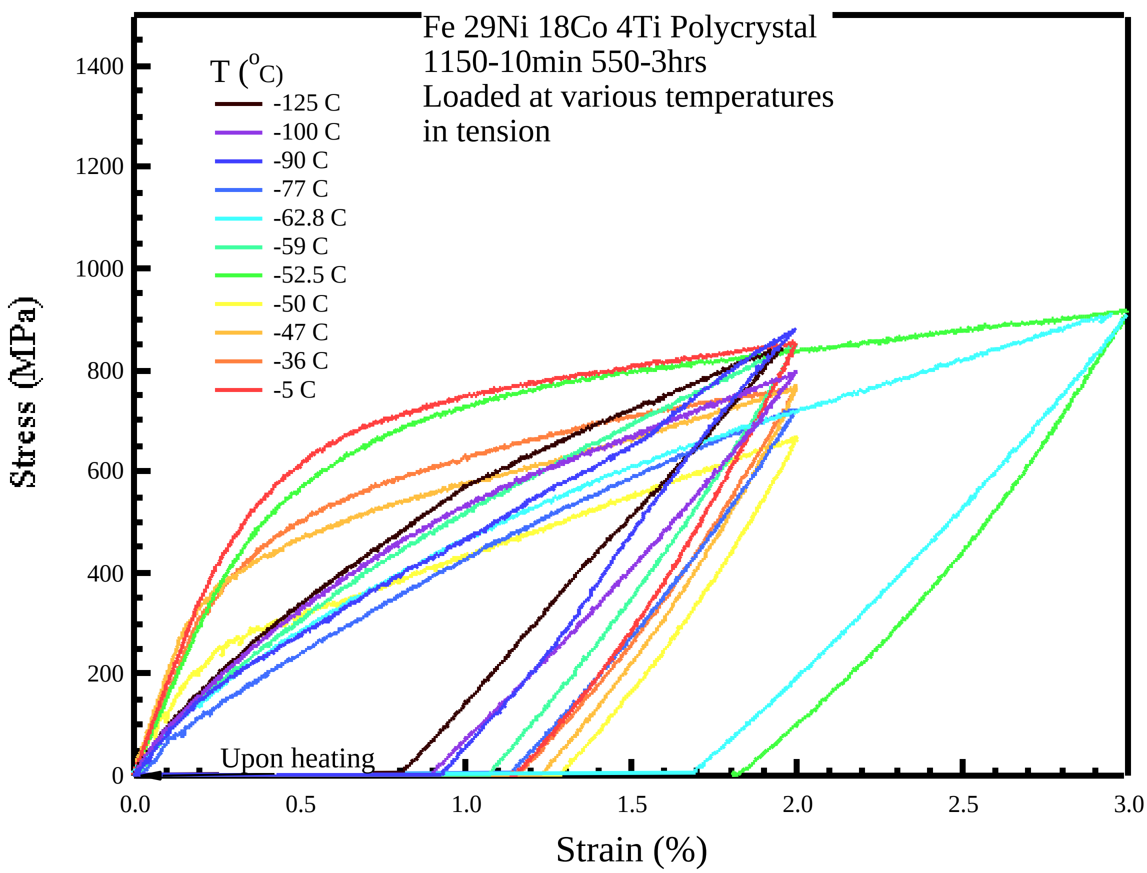
Schematic of Stress-Strain Response and Shape Recovery in FeNiCoTi alloys, $T<M_f$



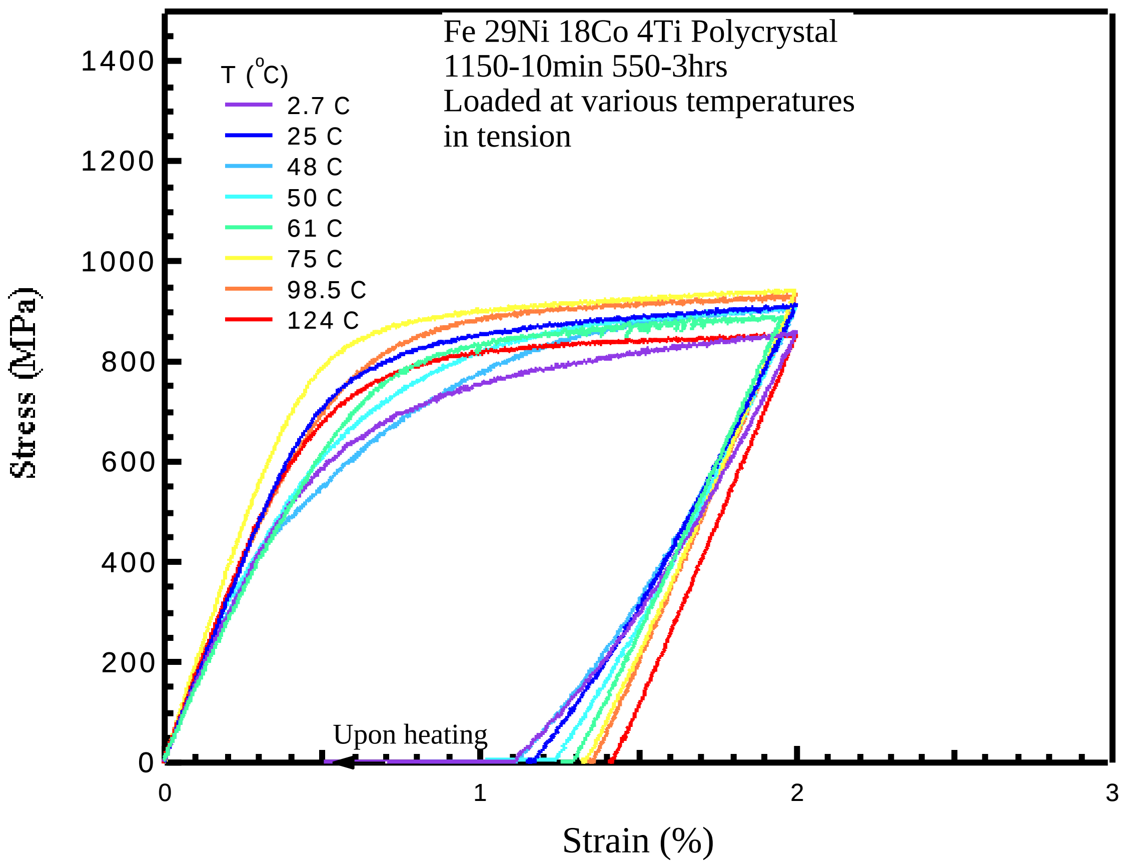
Schematic of Stress-Strain Response and Shape Recovery in FeNiCoTi alloys, $T>A_s$



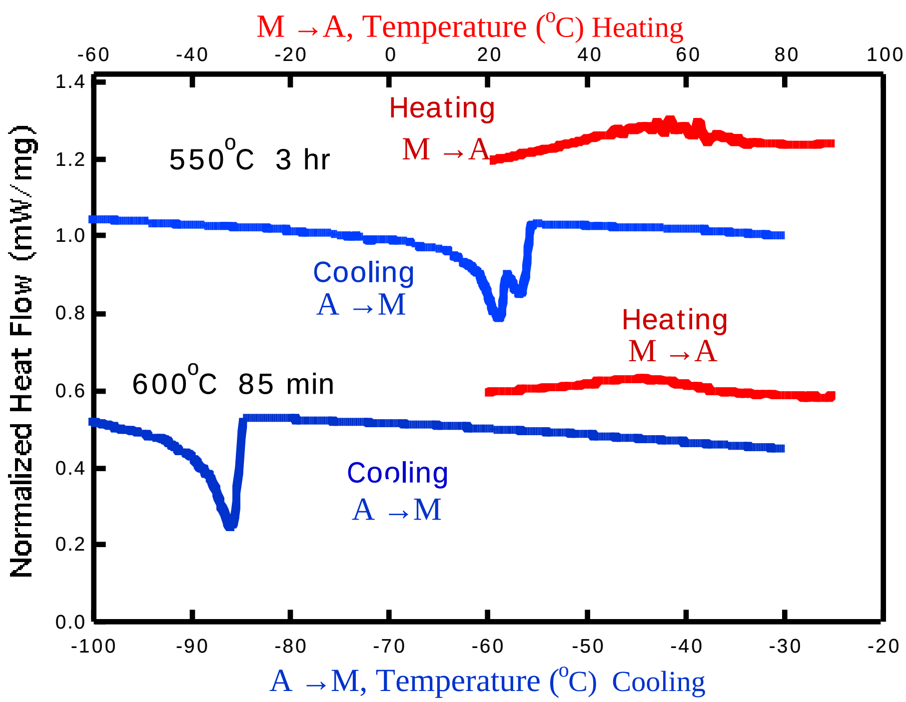
Stress-strain Response under Tension



Stress-strain Response under Tension(ctd.)



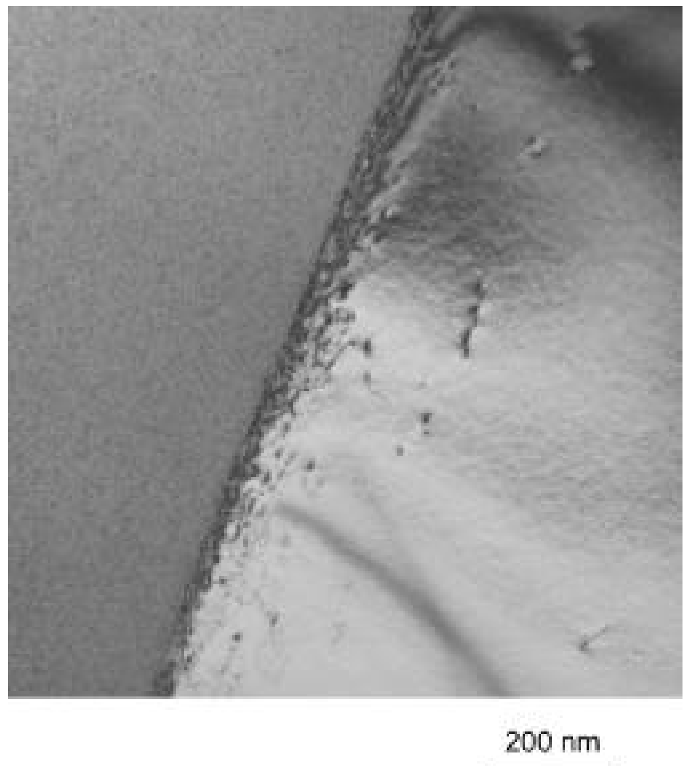
Transformation Characteristics of FeNiCoTi



$$\frac{d\Sigma}{dT} = \frac{\rho \Delta s}{\varepsilon^{trA \to M}}$$

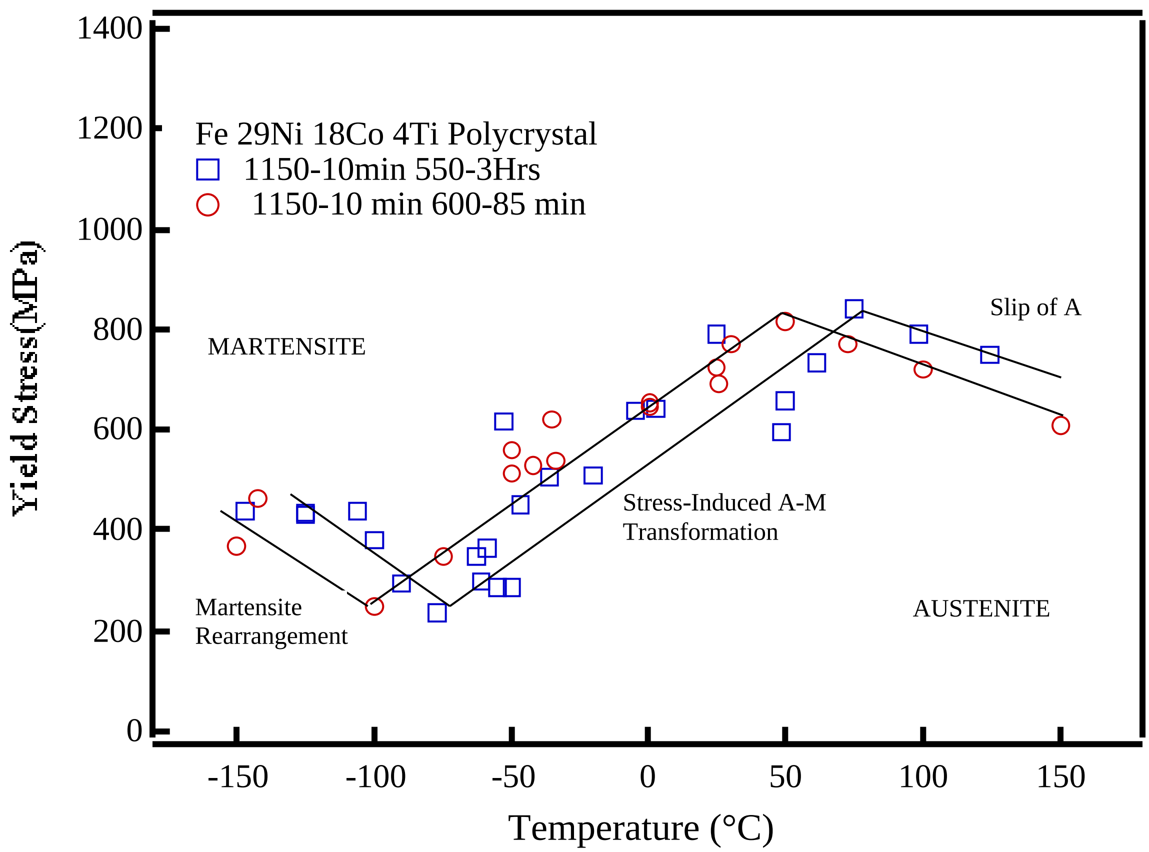
Fine Precipitates and Interface Dislocations

600°C 85min

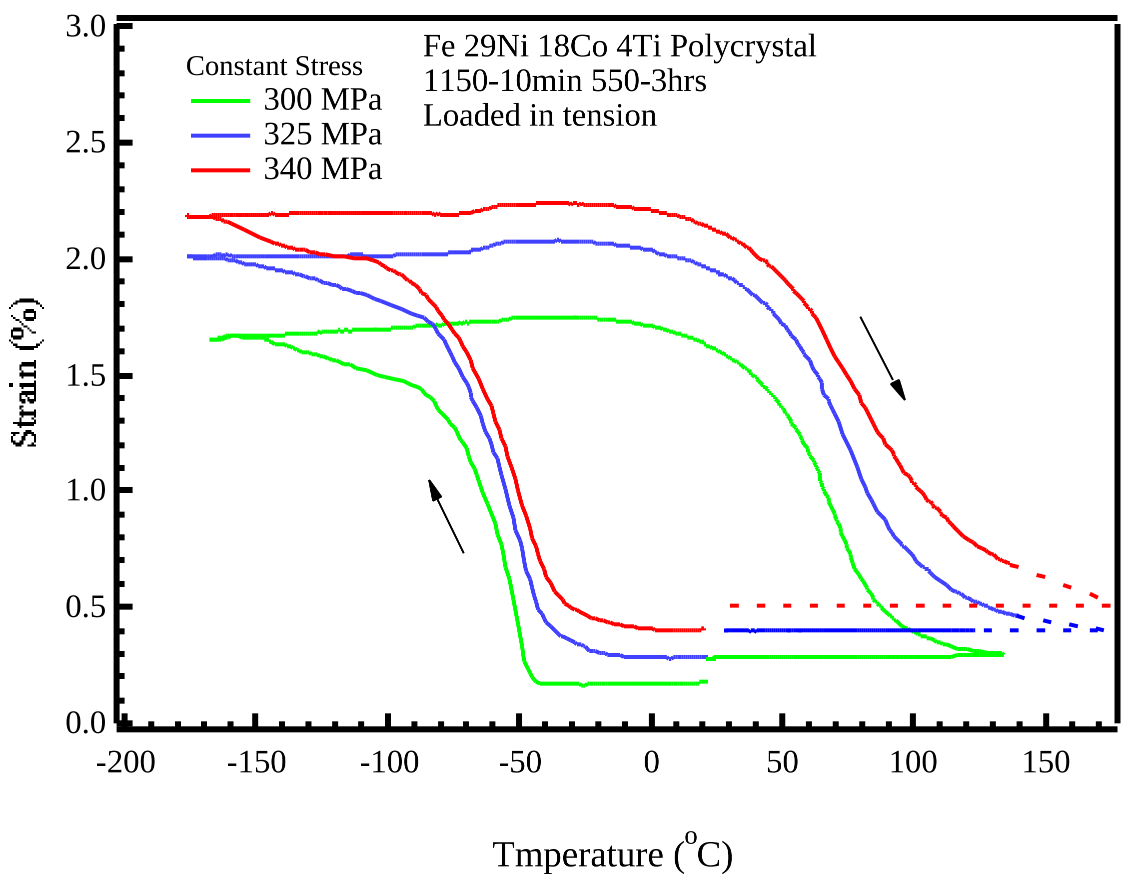


550°C 3hours

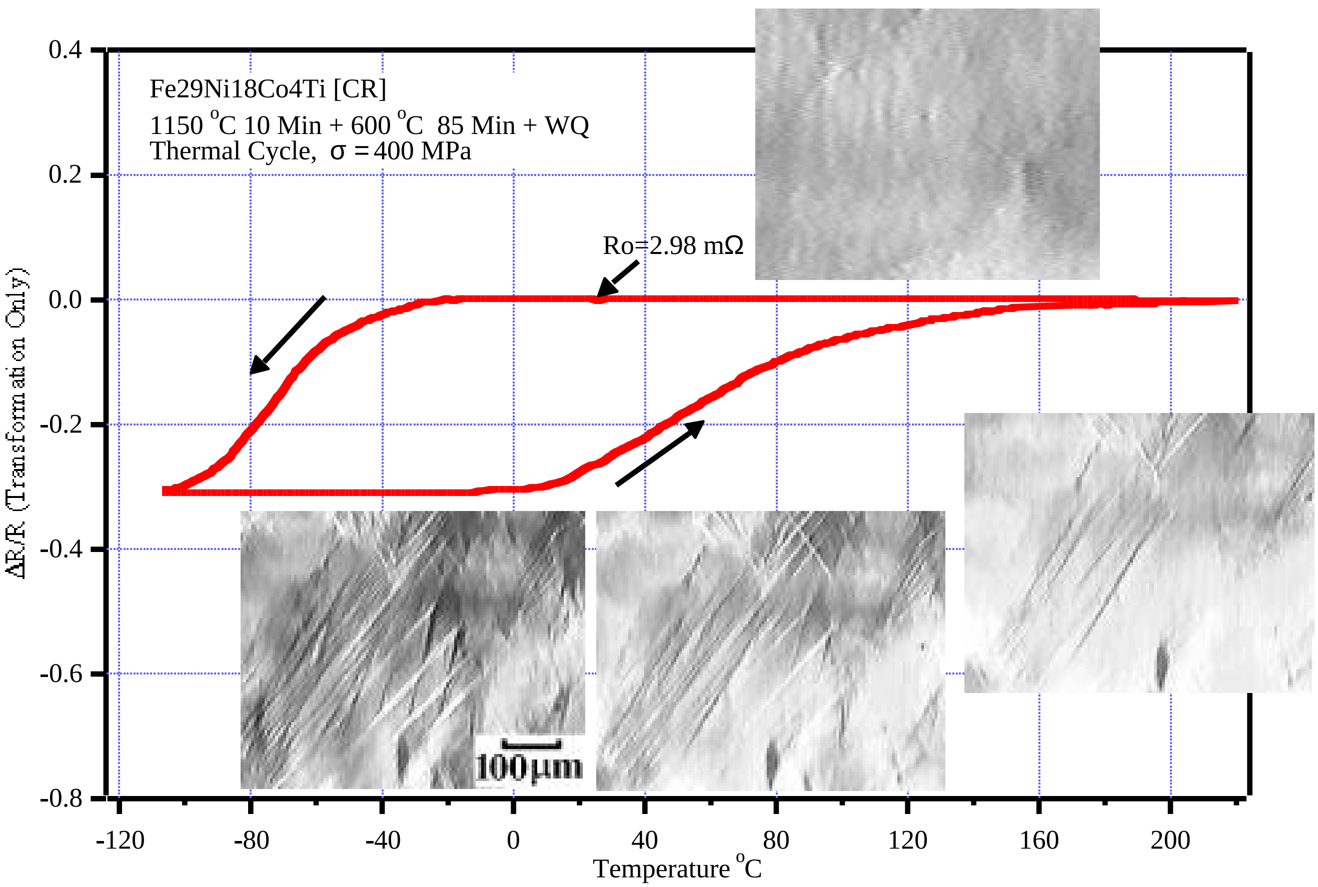
Critical Stress as a Function of Temperature



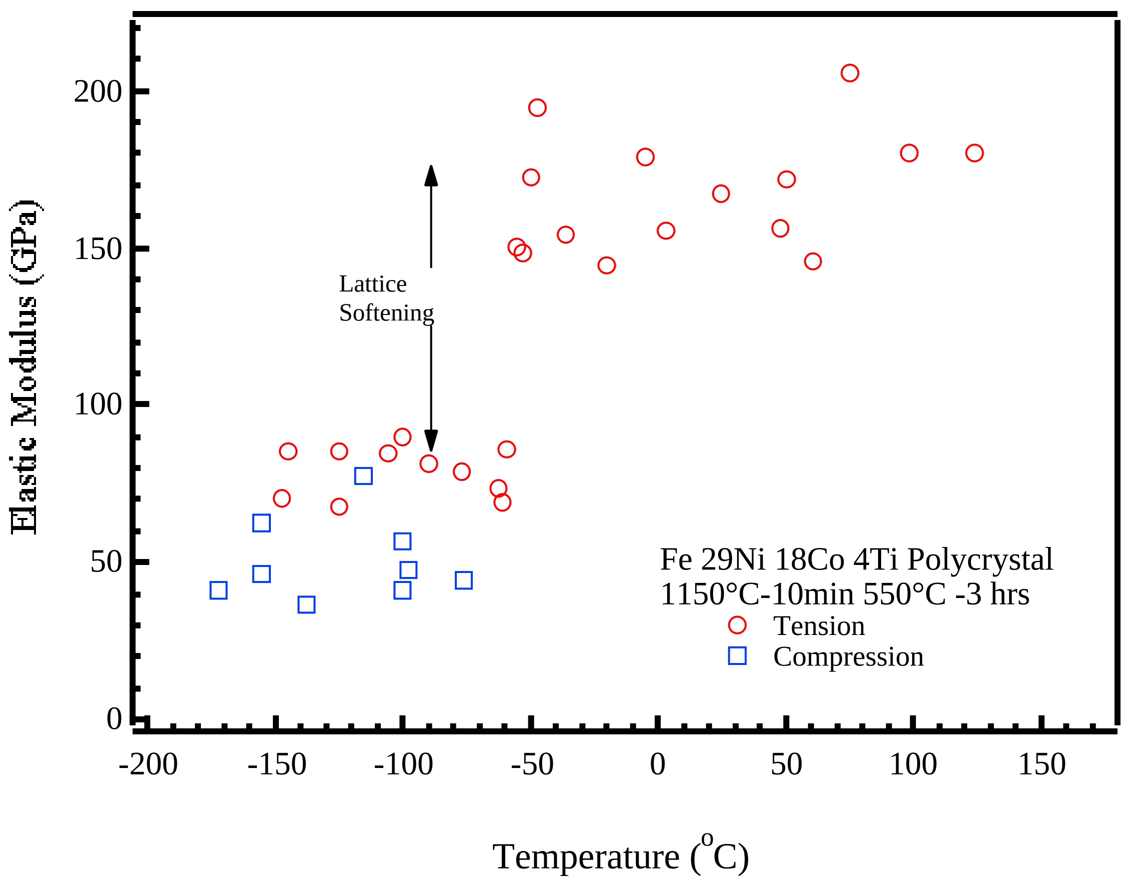
Temperature Cycling under Three Different Stress Levels



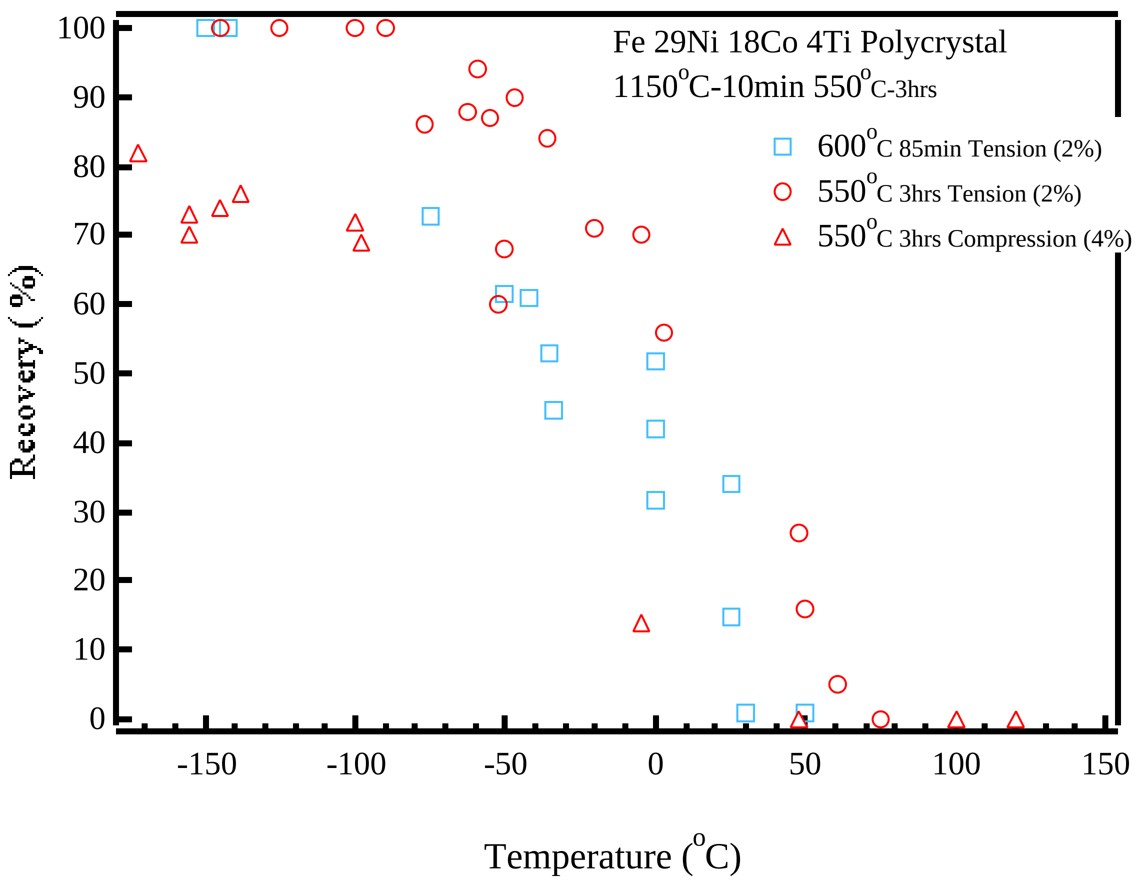
Changes in Electrical Resistance under Temperature Cycling



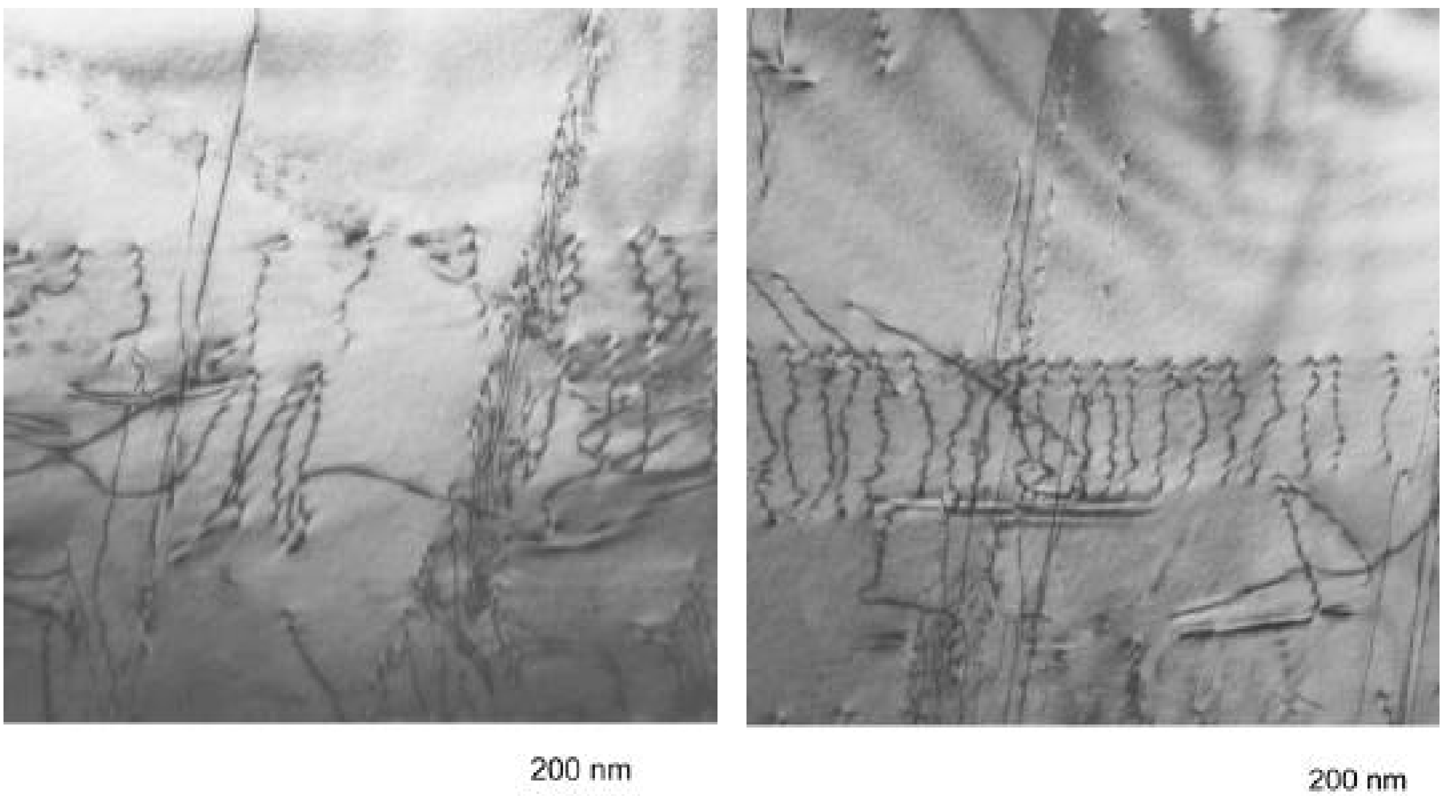
Lattice Softening Near the Transition Temperature

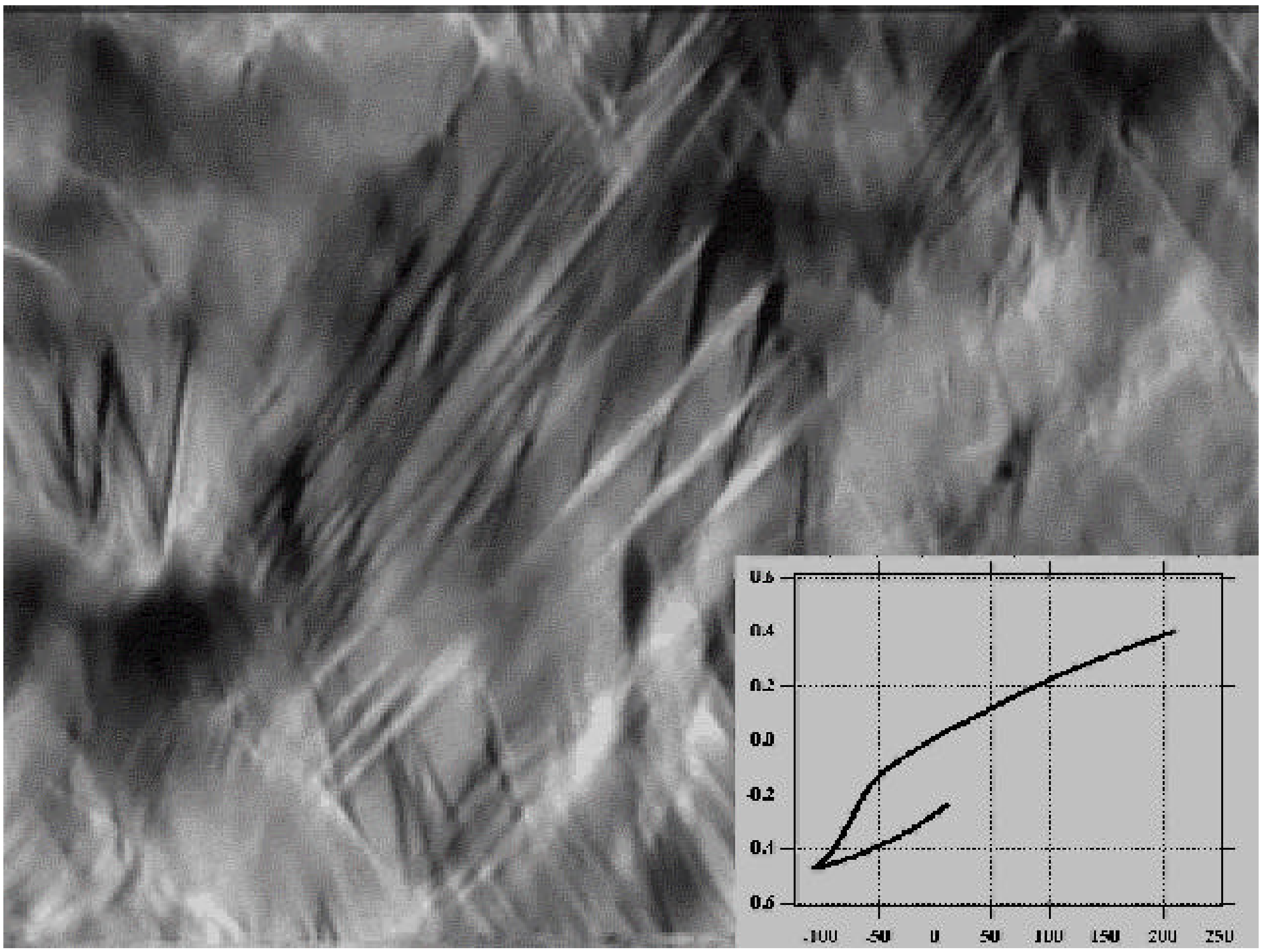


Recovery as a Function of Temperature



Evidence of Planar Slip





0.6
0.4
0.2
0.0
-0.2
0.4
0.6
-100
-50
0
50
100
150
200
250

Summary

- The Fe - based materials have higher specific strength, higher specific modulus compared to NiTi alloys.
- With texture control higher transformation strains can be attained.