Deformation of NiTiCu Shape Memory Single Crystals

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Introduction

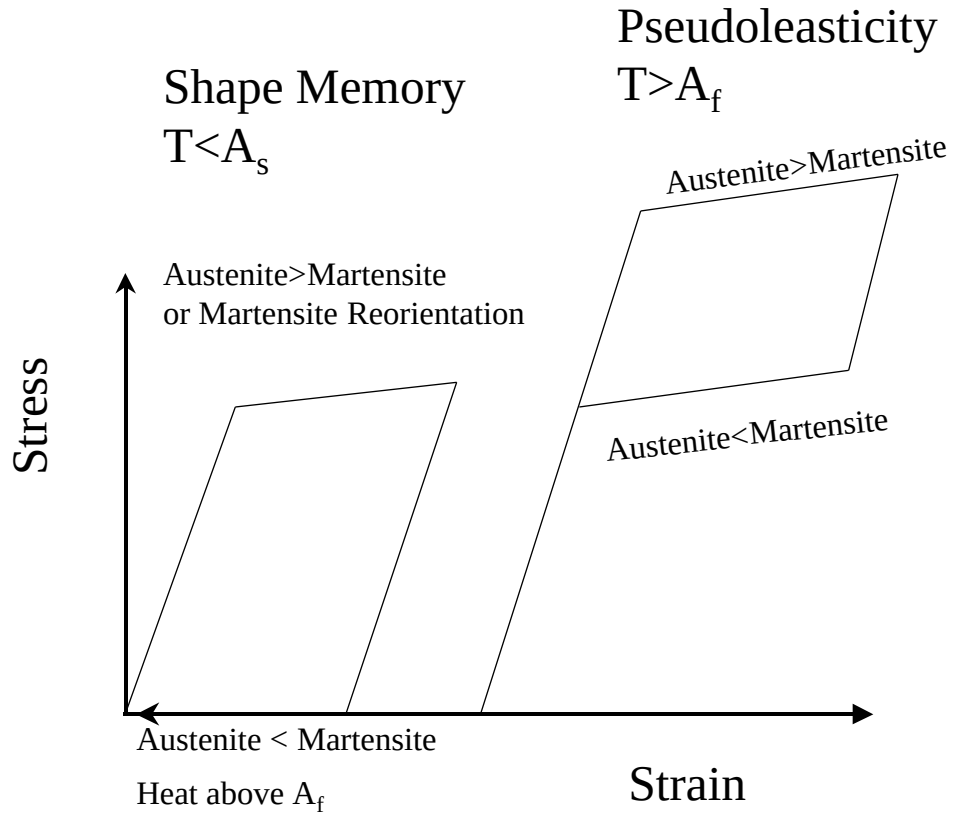
- What is Shape Memory?
- Shape memory is the ability of the material to recover large strains through a phase transformation from martensitic to austenitic crystal states upon heating

- Why ‘Single Crystals’?
- Clear understanding of SME and pseudoelasticity without GB effects.
- Permits study of the influence of plasticity in the B2 phase.
- Many of the polycrystalline NiTiCu alloys exhibit significant texture.

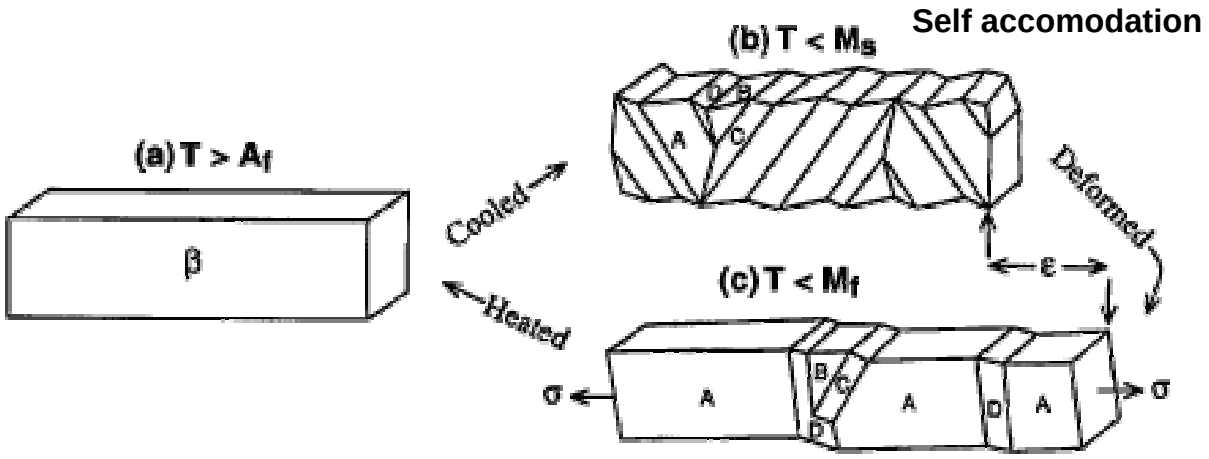
- Why’ Seek Alternatives to NiTi’?
- To alter strength, the transformation temperature range, and eliminate aging treatments for pseudoelasticity.

- Why’ Measure electrical Resistance?
- To separate transformation from detwinning effects

What are shape memory alloys?

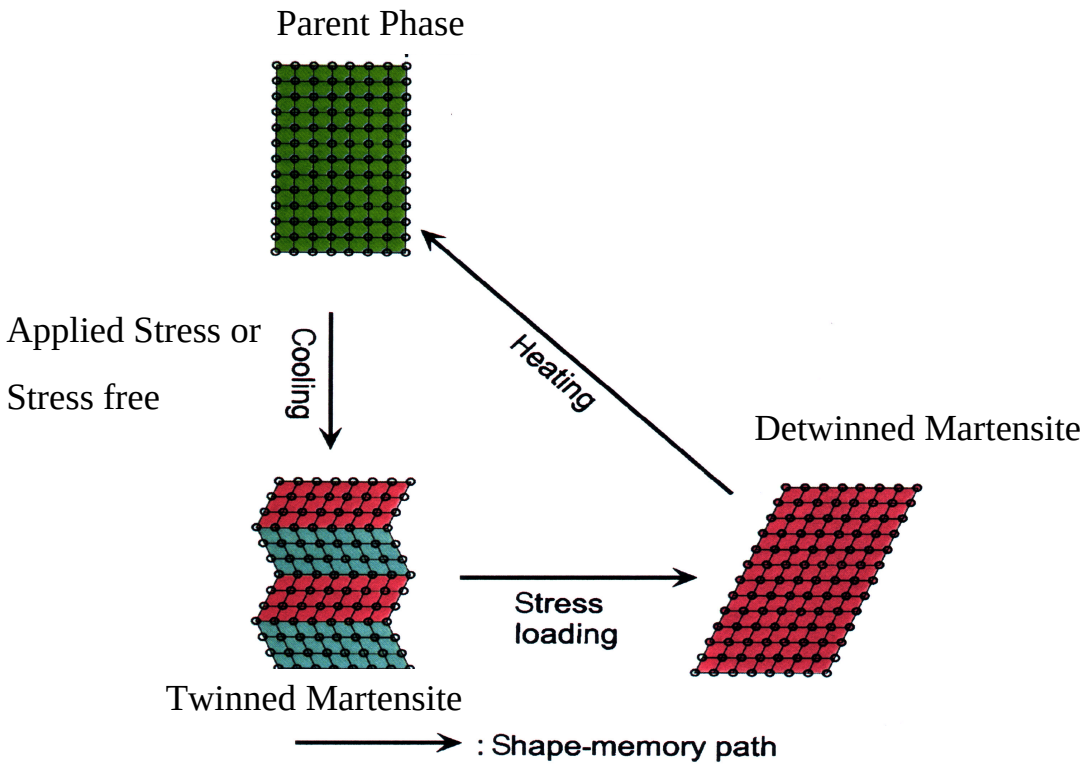


What makes them work?



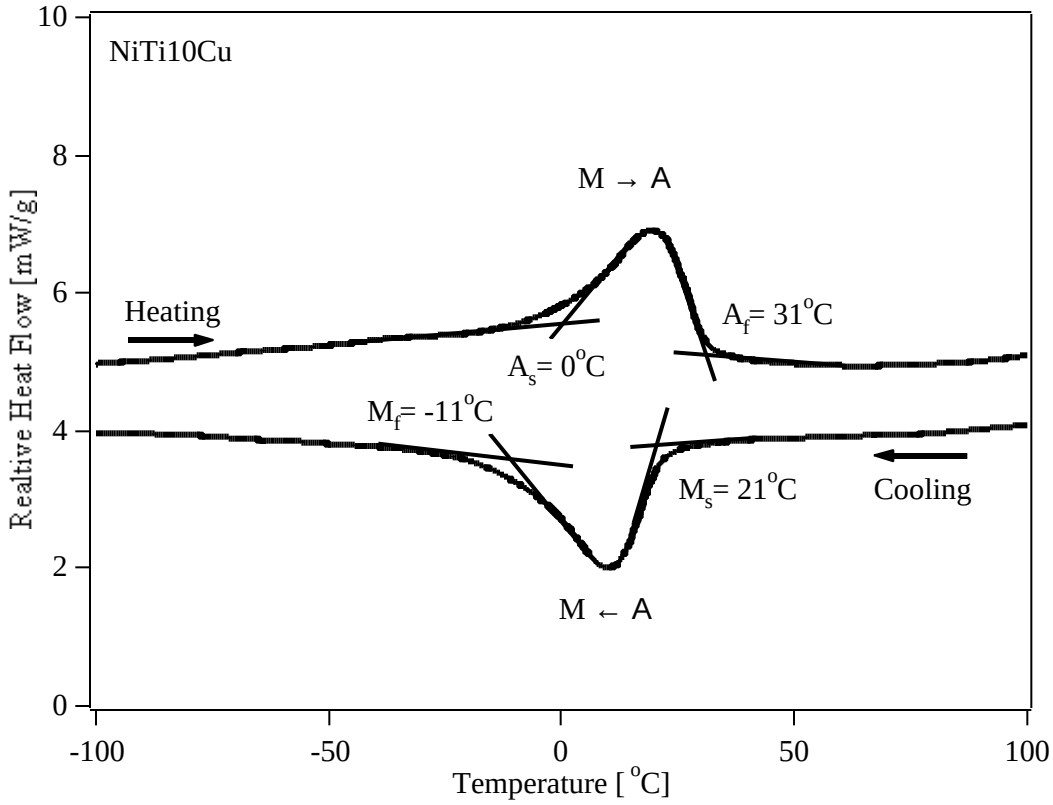
A thermal or stress induced martensitic transformation.

Schematic Illustration of The Mechanism of The Shape-Memory Effect



Adapted from Figure 1 in [1]

[1] Otsuka, K. and Kakeshita, T., *MRS Bulletin,* Feb. 2002, 91

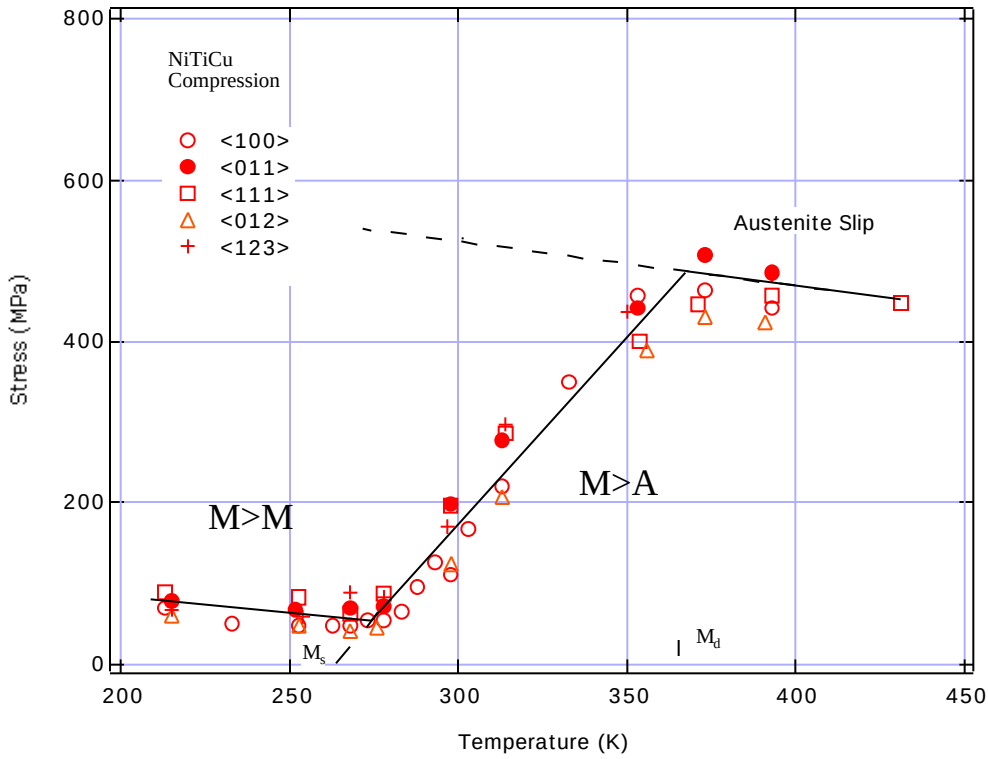

NiTi10Cu
M → A
Heating
A_f= 31°C
A_s= 0°C
M_f= -11°C
M_s= 21°C
Cooling
M ← A
Realtive Heat Flow [mW/g]
Temperature [°C]
10
8
6
4
2
0
-100
-50
0
50
100

NiTiCu Shape Memory Alloys

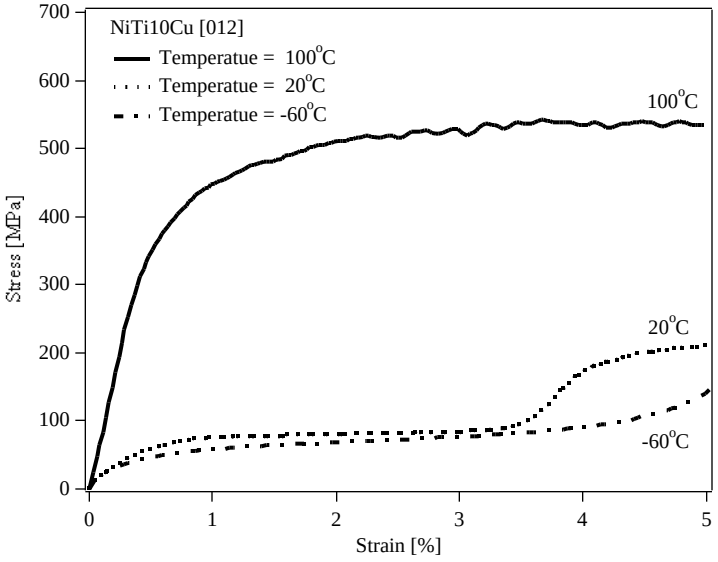
Major Features:
Stable Martensite Start Temperatures
Two Stage Transformation (B2 to B19 to B19') for near 10%Cu
Lower Transformation strains compared to NiTi
Narrower Transformation Temperature Range compared to NiTi

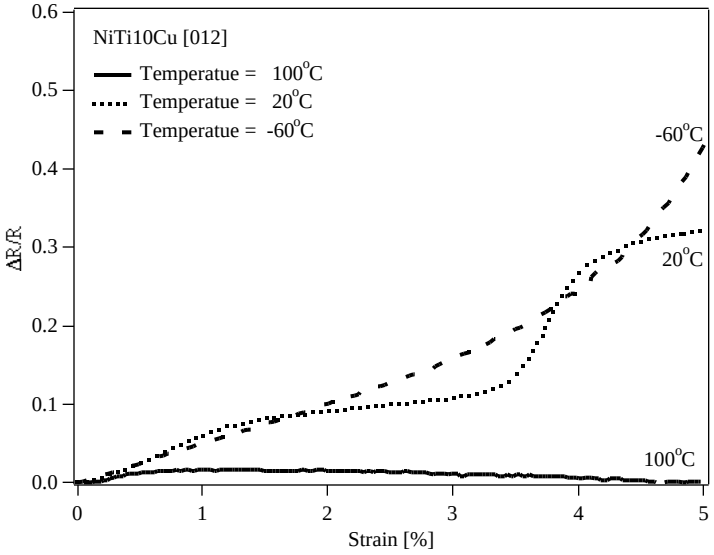
Missing Information:
Transformation Strains (Calculations and Experiments)
Single Crystal Information- Tension Compression Asymmetry,
Crystal Orientation Dependence
Clear Understanding of Two Stages of Transformation (B2 B19 B19')
The Role of Detwinning of B19'

Critical Stress versus Temperature (NiTi10Cu)

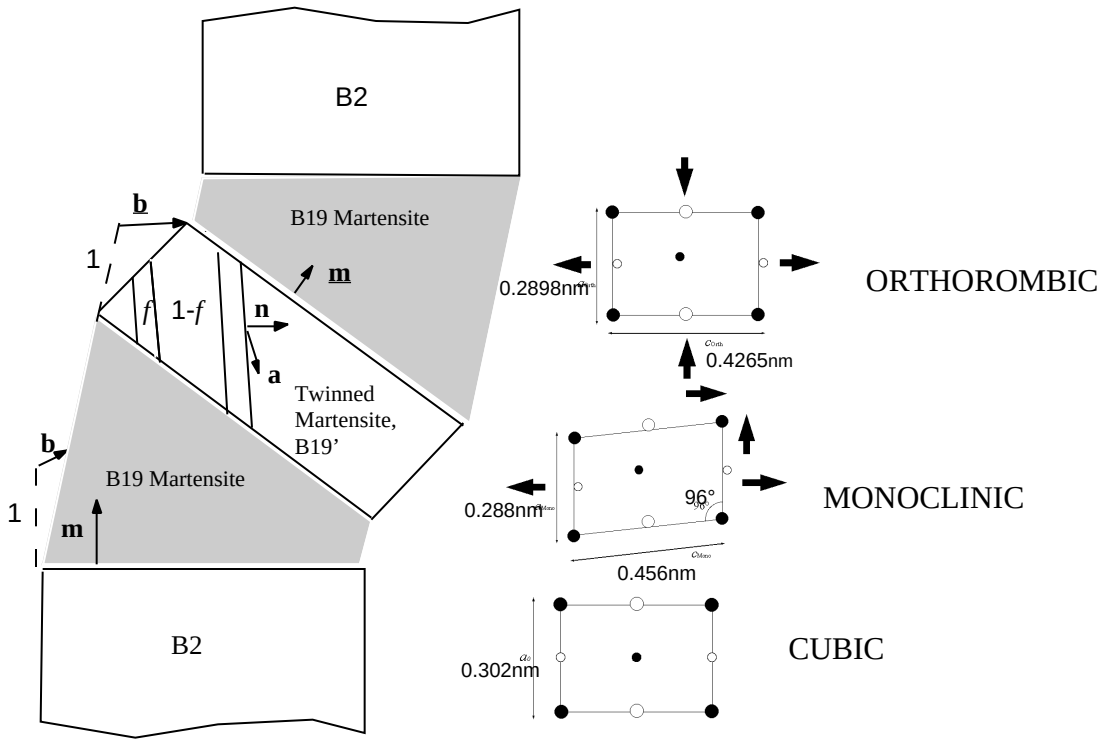


H. Sehitoglu et al. Met. Mats. Trans.,2001, 32A, 477-489


NiTi10Cu [012]
Temperatue = 100°C
Temperatue = 20°C
Temperatue = -60°C
100°C
20°C
-60°C
Stress [MPa]
Strain [%]
0
100
200
300
400
500
600
700
0
1
2
3
4
5


NiTi10Cu [012]
Temperatue = 100°C
Temperatue = 20°C
Temperatue = -60°C
-60°C
20°C
100°C
ΔR/R
Strain [%]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0
1
2
3
4
5

Two Stage Transformation in NiTiCu- Schematic



Cubic to Ortohorombic Transformation

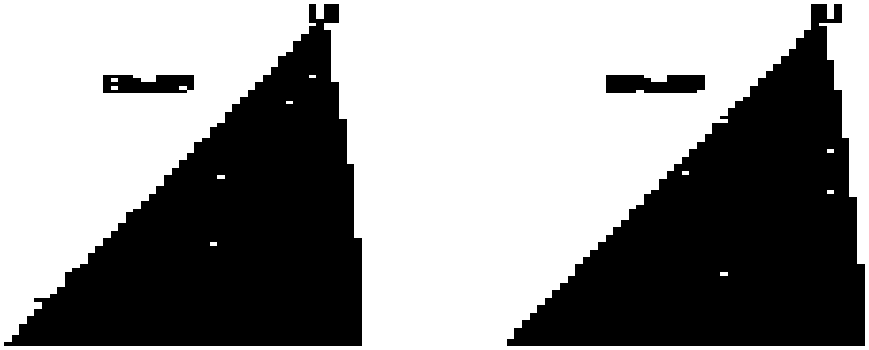
$$\varepsilon_1 = \frac{1}{2}(\mathbf{F}_{\mathbf{Orth}}^{\mathbf{T}} \ \mathbf{F}_{\mathbf{Orth}} - \mathbf{I}) = \frac{1}{2}[\mathbf{b} \quad \mathbf{m} + \mathbf{m} \quad \mathbf{b} + (\mathbf{b} \ \mathbf{b})\mathbf{m} \quad \mathbf{m}]$$

Ortohorombic to Monoclinic Transformation

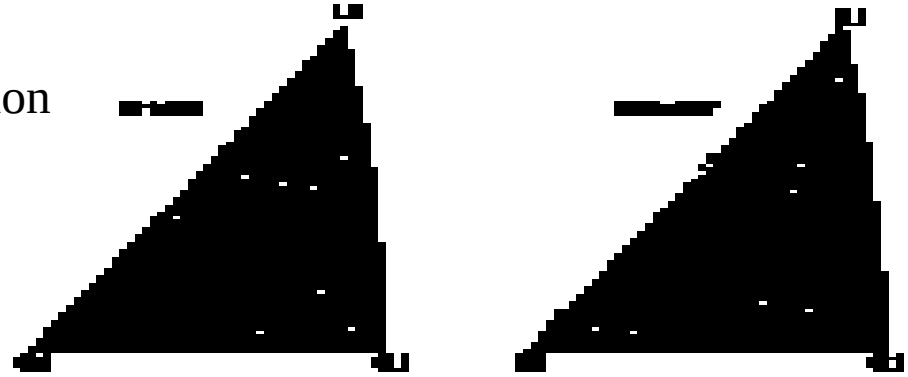
$$\varepsilon_2 = \frac{1}{2}[(\mathbf{F}_{\mathrm{Mono}}\mathbf{F}_{\mathrm{Orth}}^{-1})^T \ (\mathbf{F}_{\mathrm{Mono}}\mathbf{F}_{\mathrm{Orth}}^{-1}) - \mathbf{I}] = \frac{1}{2}[\bar{\mathbf{b}} \quad \bar{\mathbf{m}}' + \bar{\mathbf{m}}' \quad \bar{\mathbf{b}} + (\bar{\mathbf{b}} \ \bar{\mathbf{b}})\bar{\mathbf{m}}' \quad \bar{\mathbf{m}}']$$

NiTiCu (10%Cu)

Tension



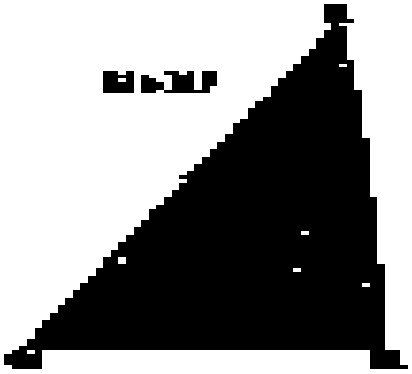
Compression



Sehitoglu et al. (2001), Acta Mater., 49, 3621-3634 (image visible upon printing)

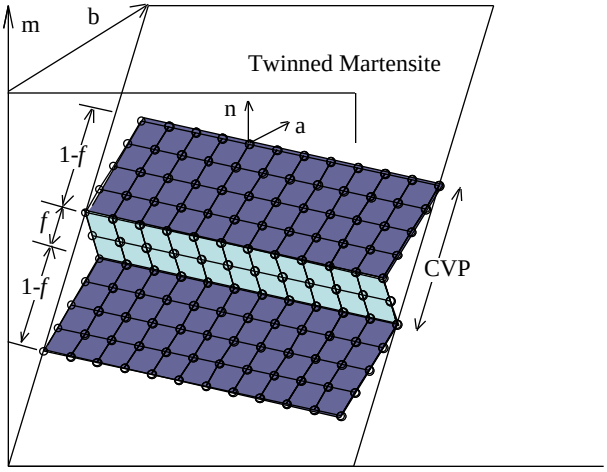
Single Step Transformation (B2 to B19’)

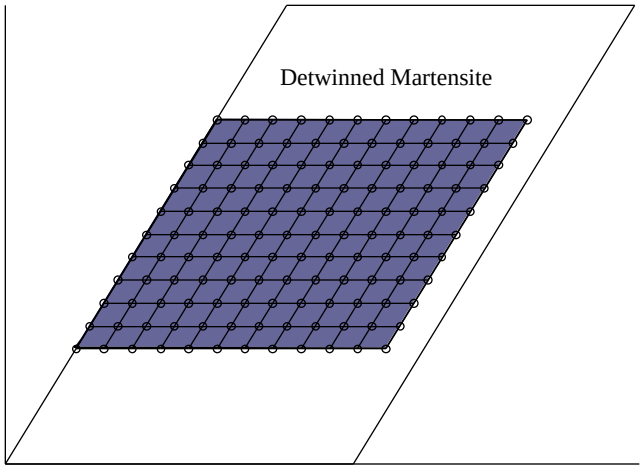
Tension



Compression

Schematic of Variants, Habit Planes, Twins, CVPs

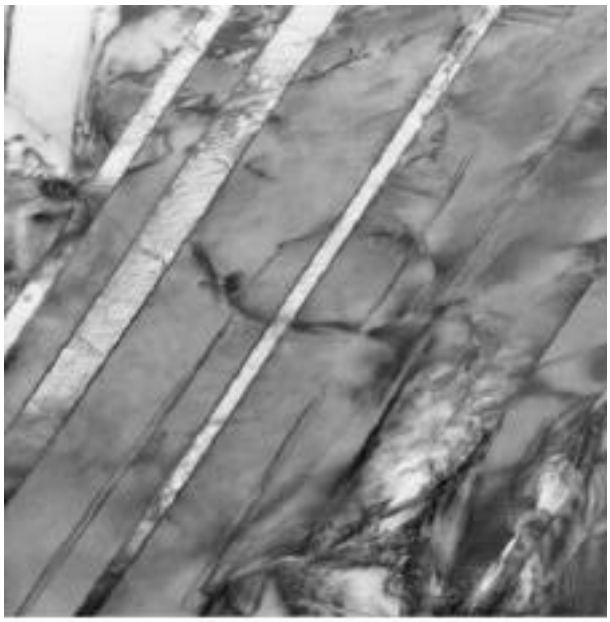


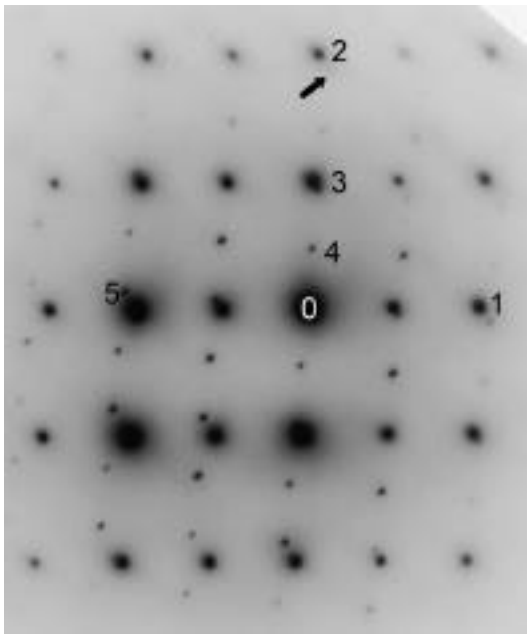


	Two Step Transformation		Single Step Transformation	B19' Detwinning	
	B2→B19 cubic→ orthorhombic	B19→B19' orthorhombic→ monoclinic	B2→B19' cubic→ monoclinic	Single Step	Two Steps
[111]	2.55	3.49	7.05	8.67	8.33
[001]	2.78	0.70	2.98	2.98	3.49
[122]	4.64	2.60	7.83	9.39	8.71
[012]	5.01	0.41	5.32	6.19	6.32
[011]	5.57	0.44	5.87	7.00	7.14

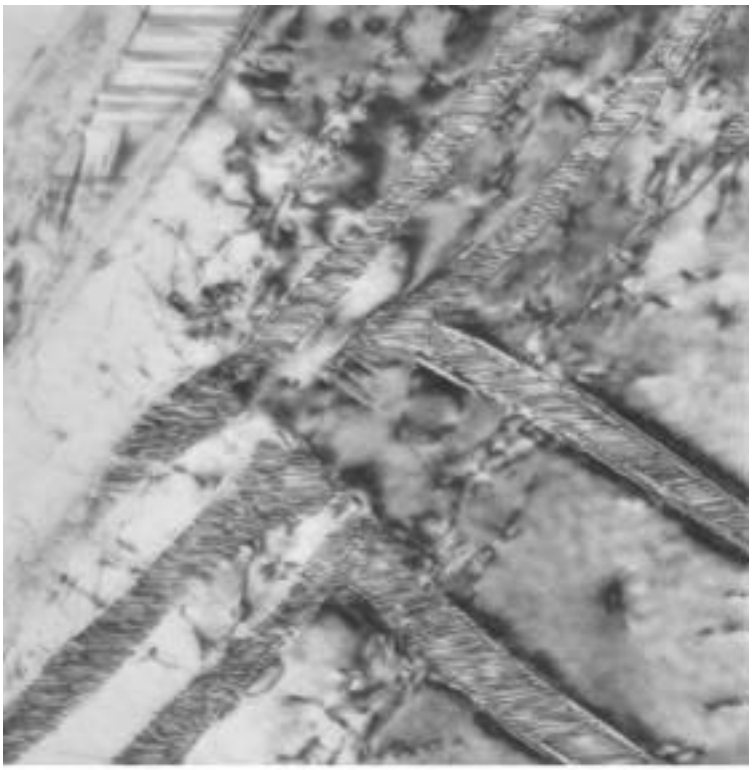
Table 1 Transformation Strains Under Tension(in percent)

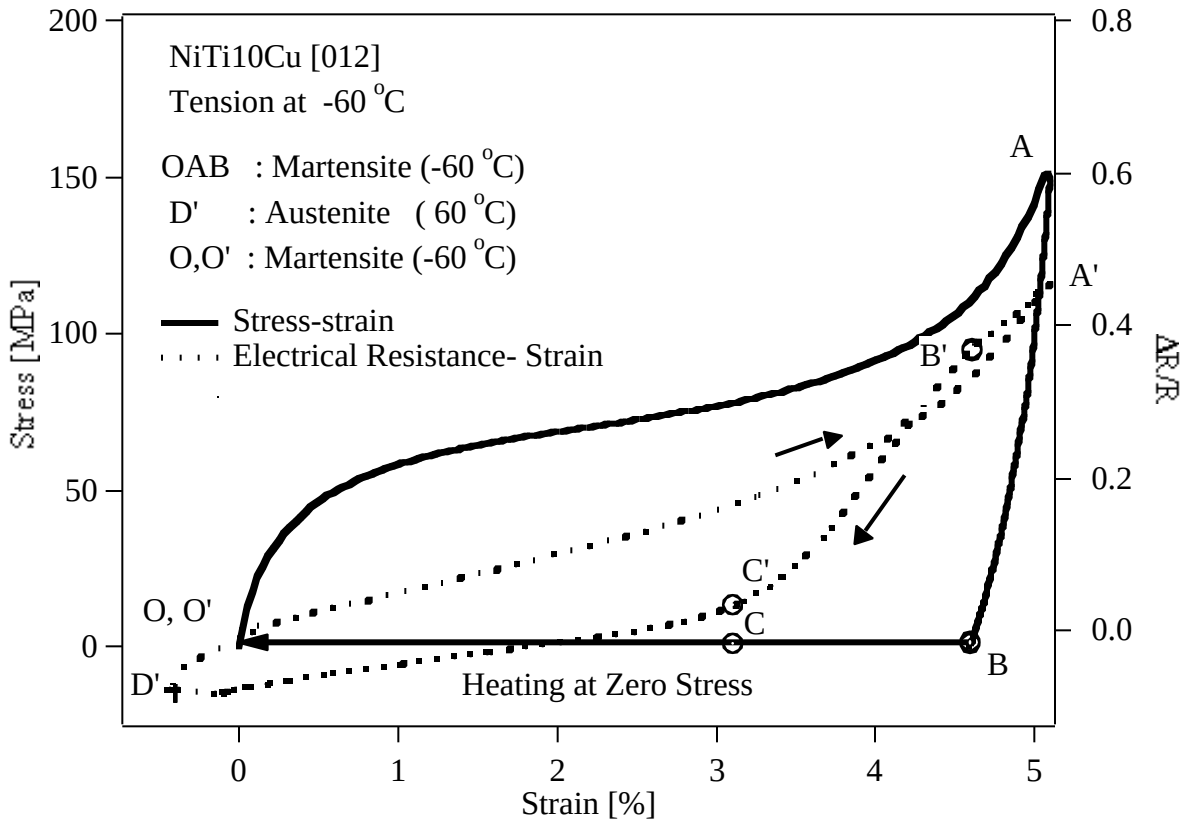
Monoclinic/Orthorombic Structure in Martensite in NiTiCu

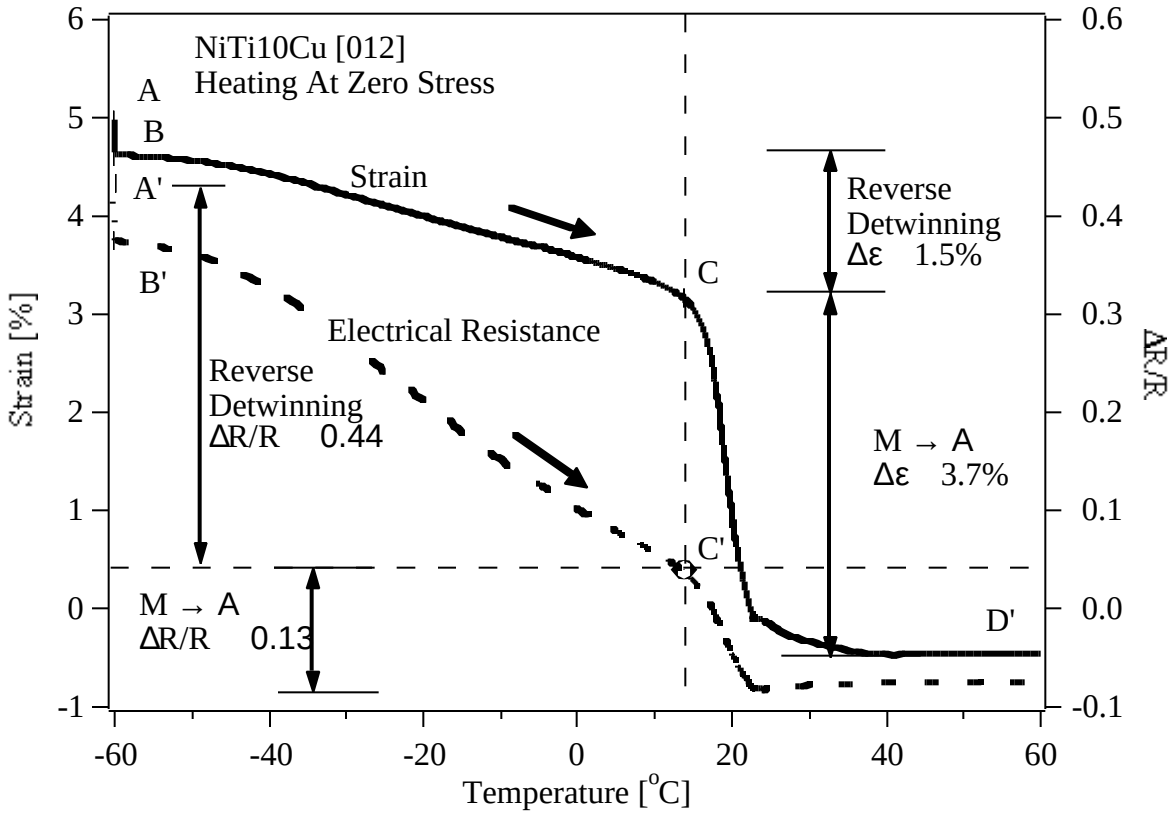


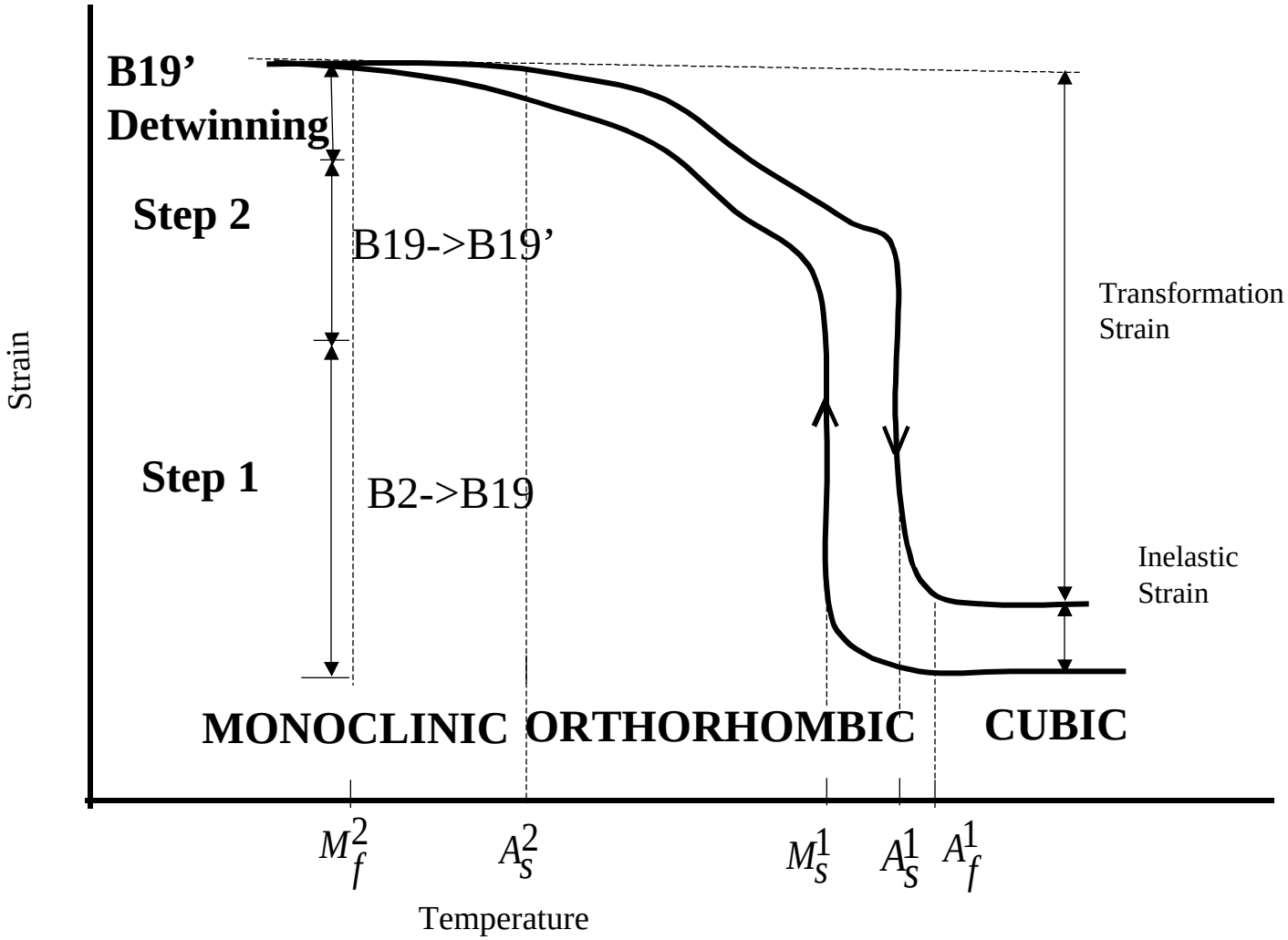


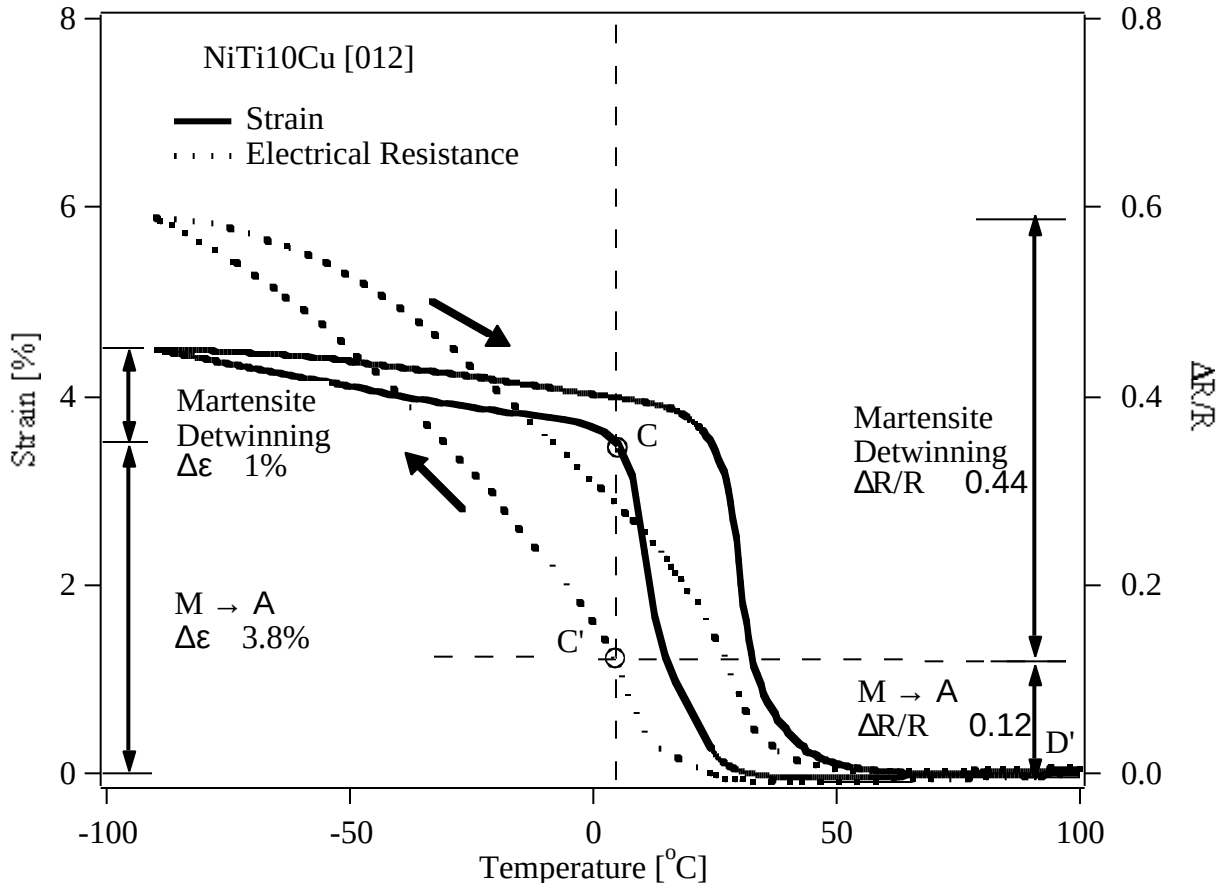
Internally Twinned Martensite



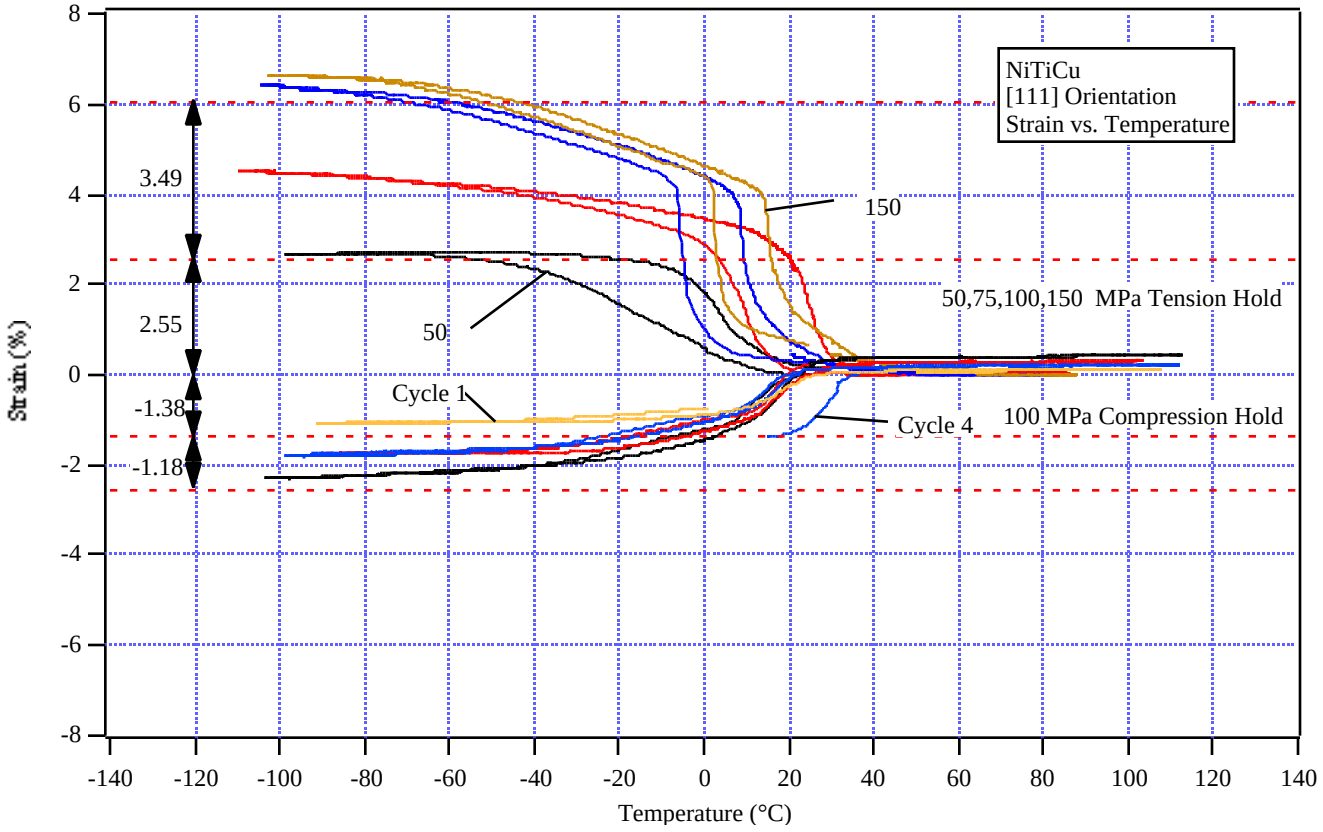

NiTi10Cu [012]
Tension at -60 °C
OAB : Martensite (-60 °C)
D' : Austenite (60 °C)
O,O' : Martensite (-60 °C)
Stress-strain
Electrical Resistance- Strain
A
A'
B'
B
C'
C
O, O'
D'
Heating at Zero Stress
Stress [MPa]
ΔR/R
Strain [%]
200
150
100
50
0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5


NiTi10Cu [012]
Heating At Zero Stress
A
B
A'
B'
C
C'
D'
Strain
Electrical Resistance
Reverse
Detwinning
ΔR/R 0.44
M → A
ΔR/R 0.13
Reverse
Detwinning
Δε 1.5%
M → A
Δε 3.7%
Strain [%]
ΔR/R
Temperature [°C]
6
5
4
3
2
1
0
-1
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-60
-40
-20
0
20
40
60

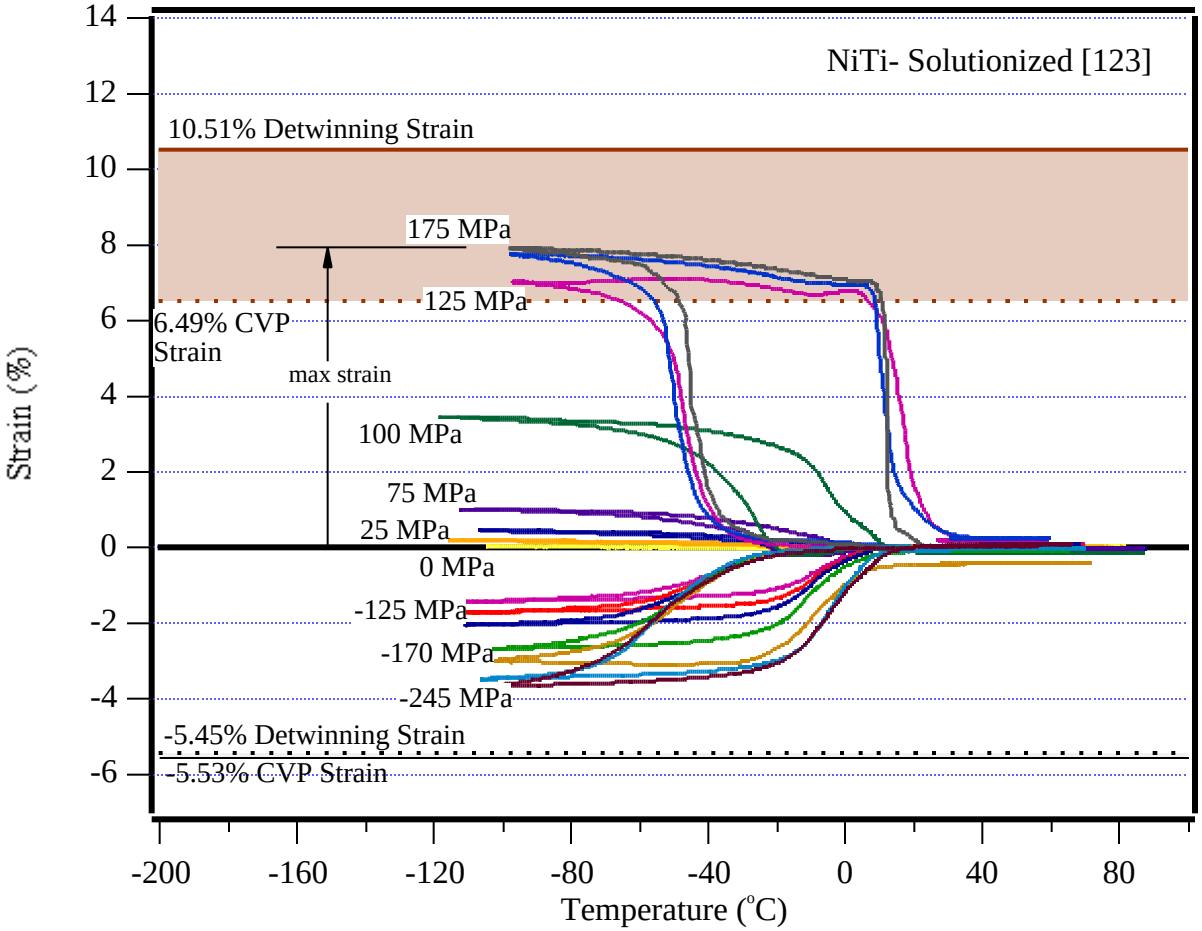

B19'
Detwinning
Step 2
B19->B19'
Step 1
B2->B19
Transformation
Strain
Inelastic
Strain
Strain
MONOCLINIC
ORTHORHOMBIC
CUBIC
M_f^2
A_s^2
M_s^1
A_s^1
A_f^1
Temperature


NiTi10Cu [012]
Strain
Electrical Resistance
Martensite
Detwinning
Δε 1%
M → A
Δε 3.8%
C
C'
Martensite
Detwinning
ΔR/R 0.44
M → A
ΔR/R 0.12
D'
Strain [%]
ΔR/R
Temperature [°C]
8
6
4
2
0
0.8
0.6
0.4
0.2
0.0
-100
-50
0
50
100

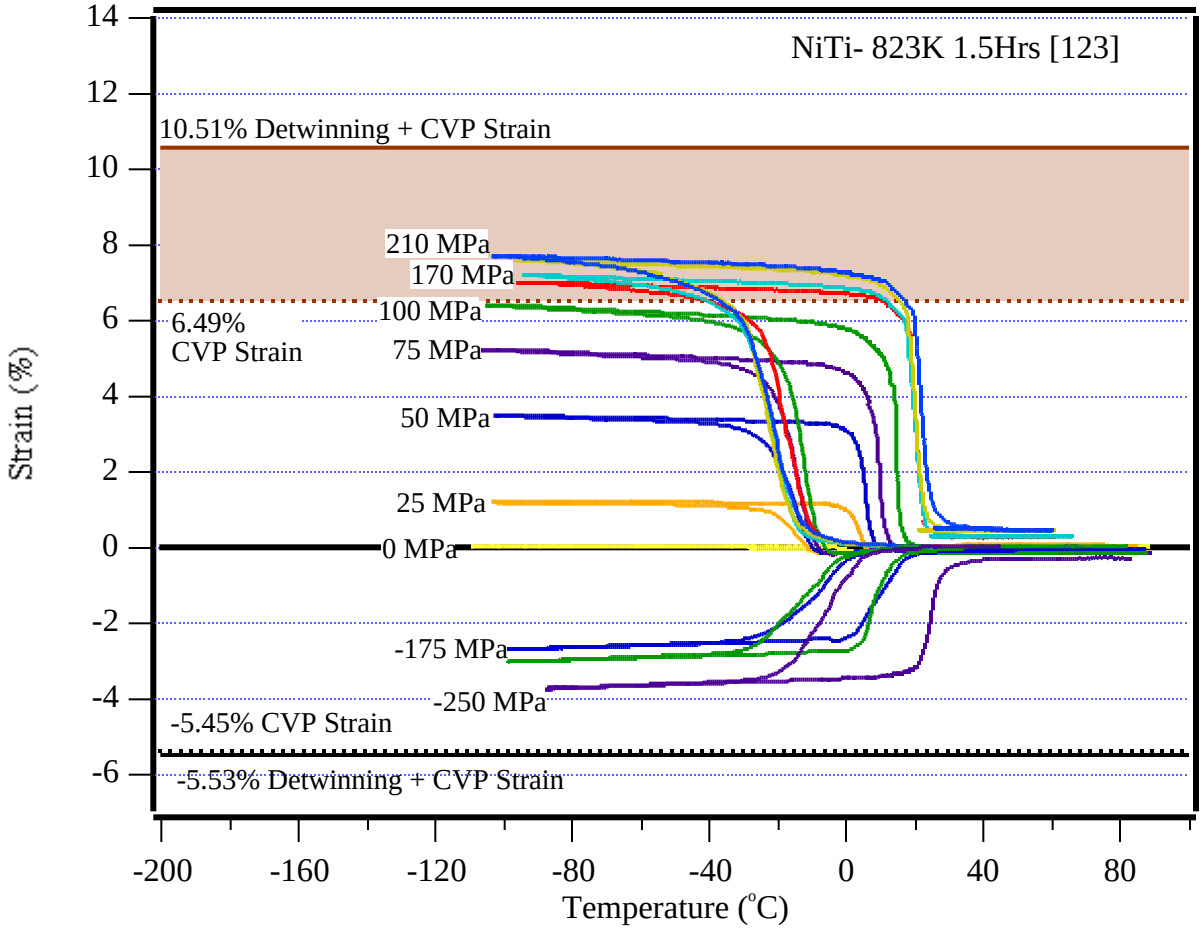
NiTiCu [111]


NiTiCu
[111] Orientation
Strain vs. Temperature
3.49
2.55
-1.38
-1.18
150
50
Cycle 1
Cycle 4
50,75,100,150 MPa Tension Hold
100 MPa Compression Hold
Strain (%)
Temperature (°C)
8
6
4
2
0
-2
-4
-6
-8
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140

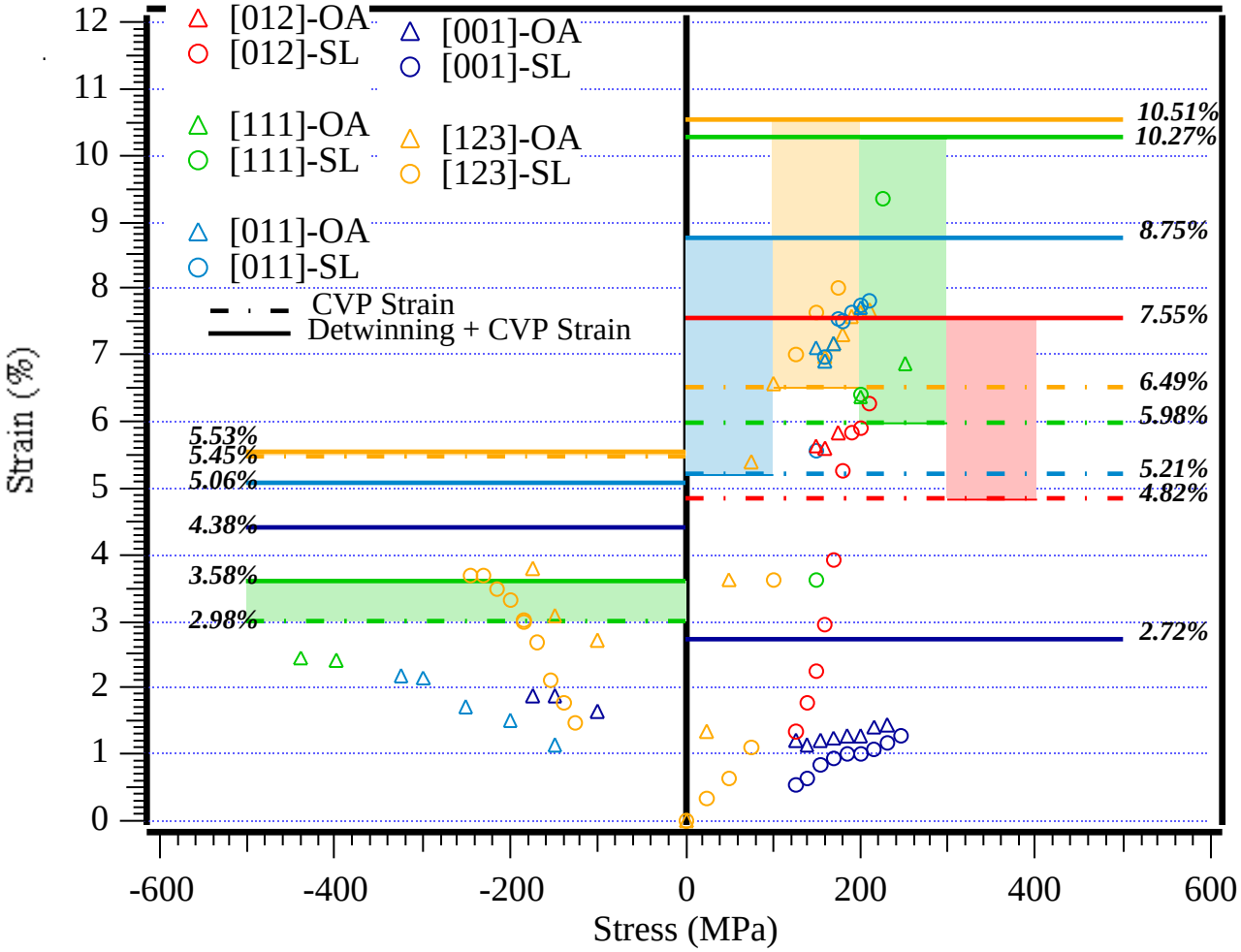
Experimental strain - temperature hysteresis curves for a solutionized Ti-50.37at%Ni [123] single crystal

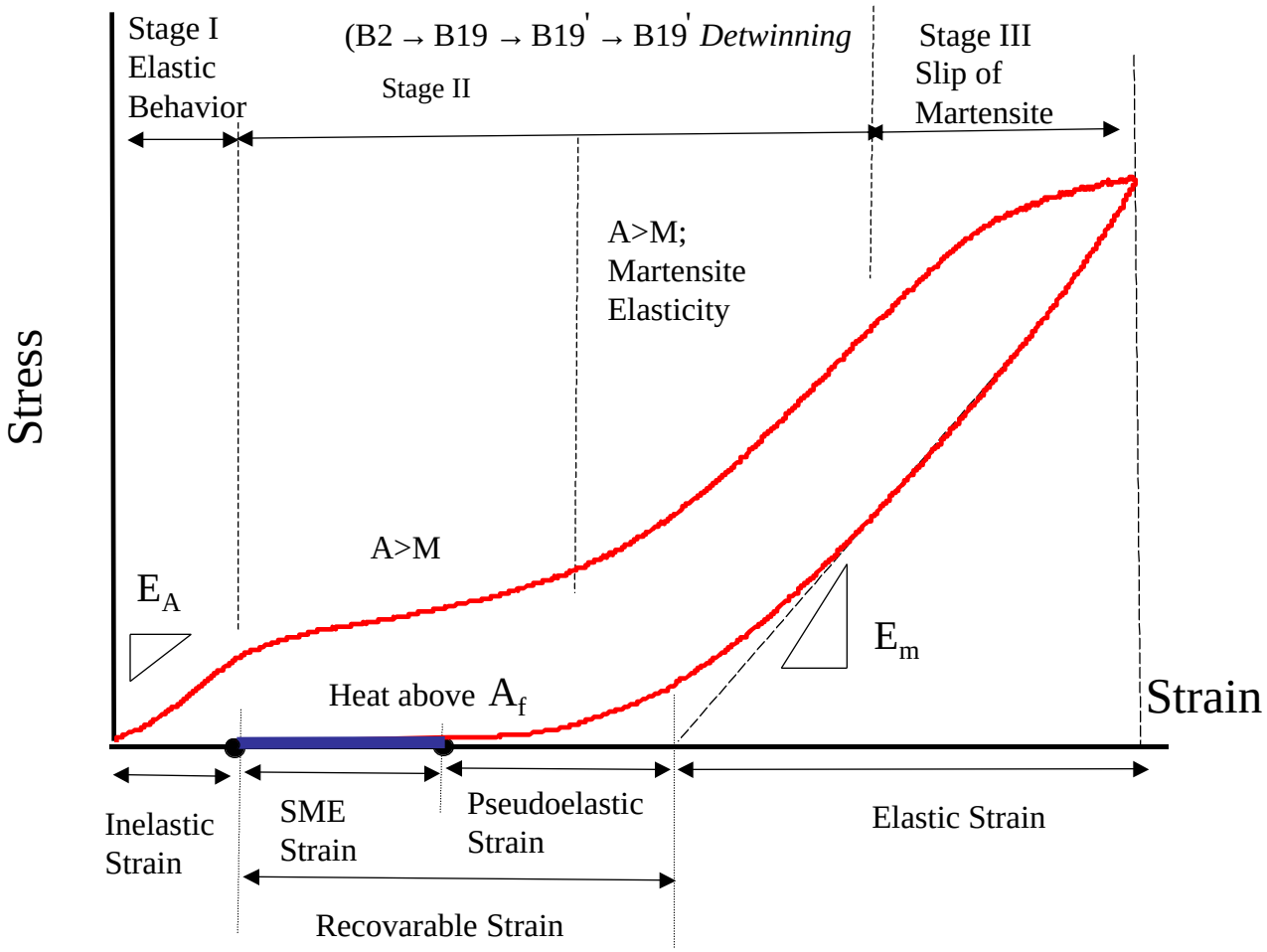


Experimental strain - temperature hysteresis curves for an aged (1.5hrs @ 823K) Ti-50.37%Ni [123] single crystal

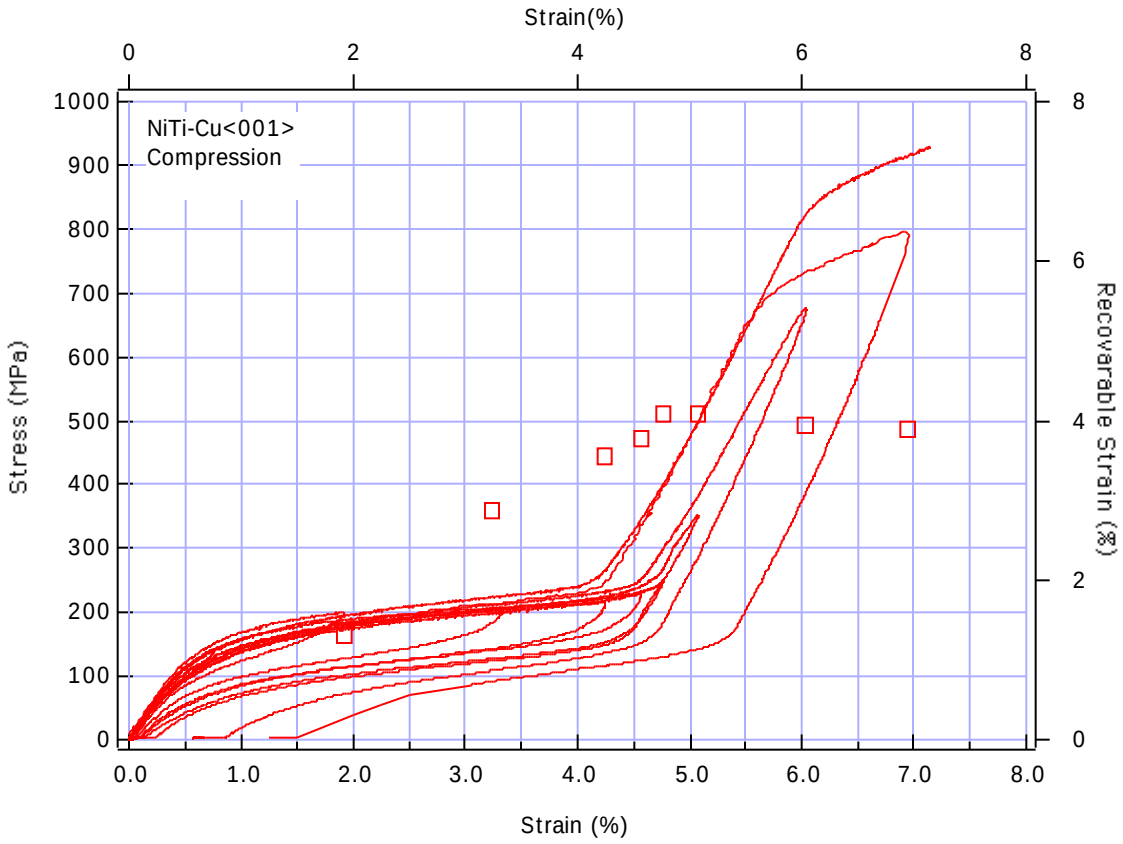


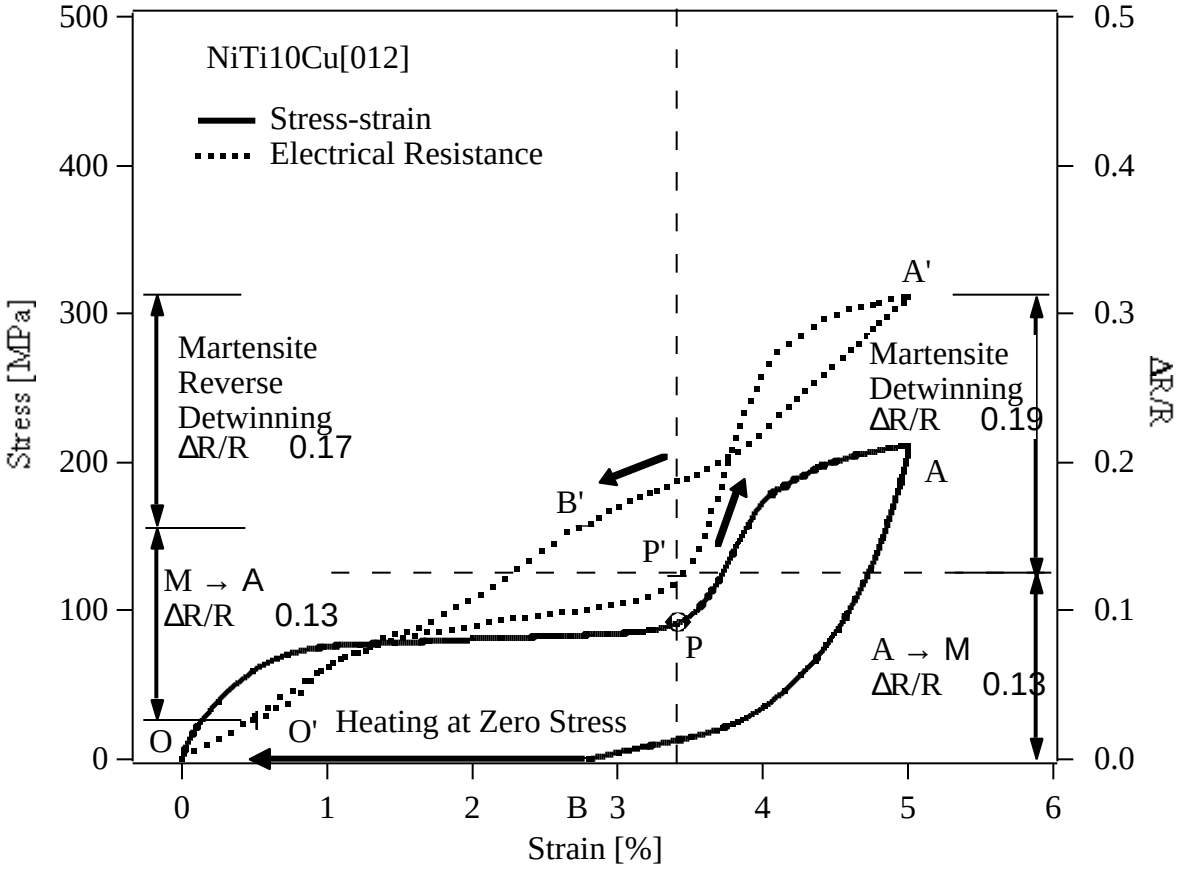
Maximum Strain (%) vs Stress (MPa) Data for Solutionized (SL) & Over-aged (OA) NiTi




Stage I
Elastic
Behavior
(B2 → B19 → B19' → B19' *Detwinning*
Stage II
Stage III
Slip of
Martensite
A>M;
Martensite
Elasticity
Stress
A>M
E_A
E_m
Heat above A_f
Strain
Inelastic
Strain
SME
Strain
Pseudoelastic
Strain
Elastic Strain
Recovarable Strain

Stress-Strain Response- Incremental Compression ,NiTi10Cu <100>




NiTi10Cu[012]
Stress-strain
Electrical Resistance
Martensite
Reverse
Detwinning
ΔR/R 0.17
M → A
ΔR/R 0.13
Martensite
Detwinning
ΔR/R 0.19
A → M
ΔR/R 0.13
Heating at Zero Stress
O
O'
P
P'
A
A'
B'
B
Stress [MPa]
ΔR/R
Strain [%]
0
100
200
300
400
500
0.0
0.1
0.2
0.3
0.4
0.5
0
1
2
3
4
5
6

Conclusions

(1) In NiTiCu alloys with 10%Cu detwinning of the martensite phase plays a significant role in deformation in addition to the two stage transformation (B19 and B19'phases).

(2) In the tensile experiments at 20 ^{o}C, the electrical resistance measurements confirmed that the end of the stress plateau region is the conclusion of the transformation and the onset of detwinning.

(3) In the tensile experiments below martensite finish temperatures (-60°C) the detwinning of the martensite variants produces a large change in resistance.

(3) The relationship between strain and electrical resistance is not linear when the electrical resistance change occurs due to both detwinning of the martensite variants and austenite to martensite transformation.