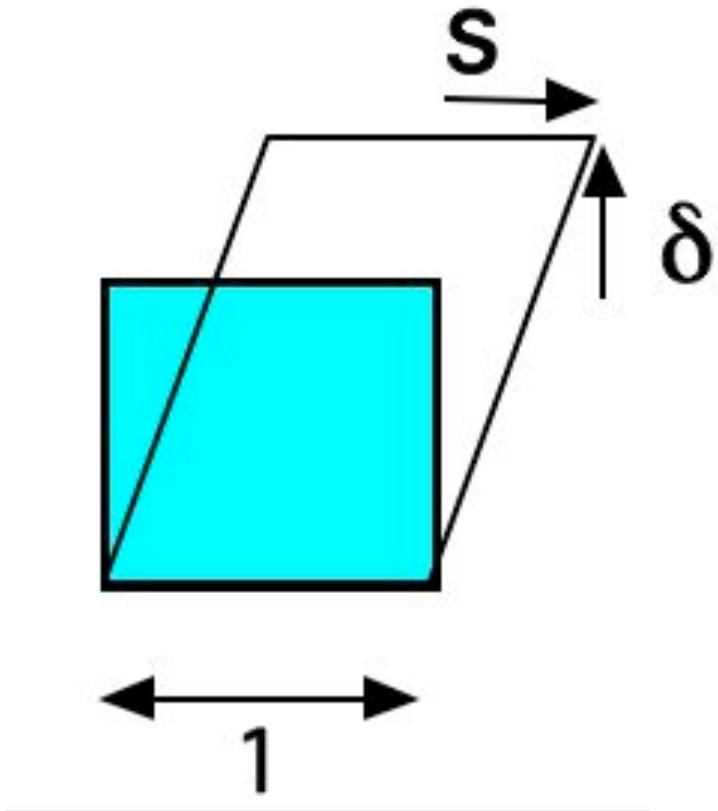
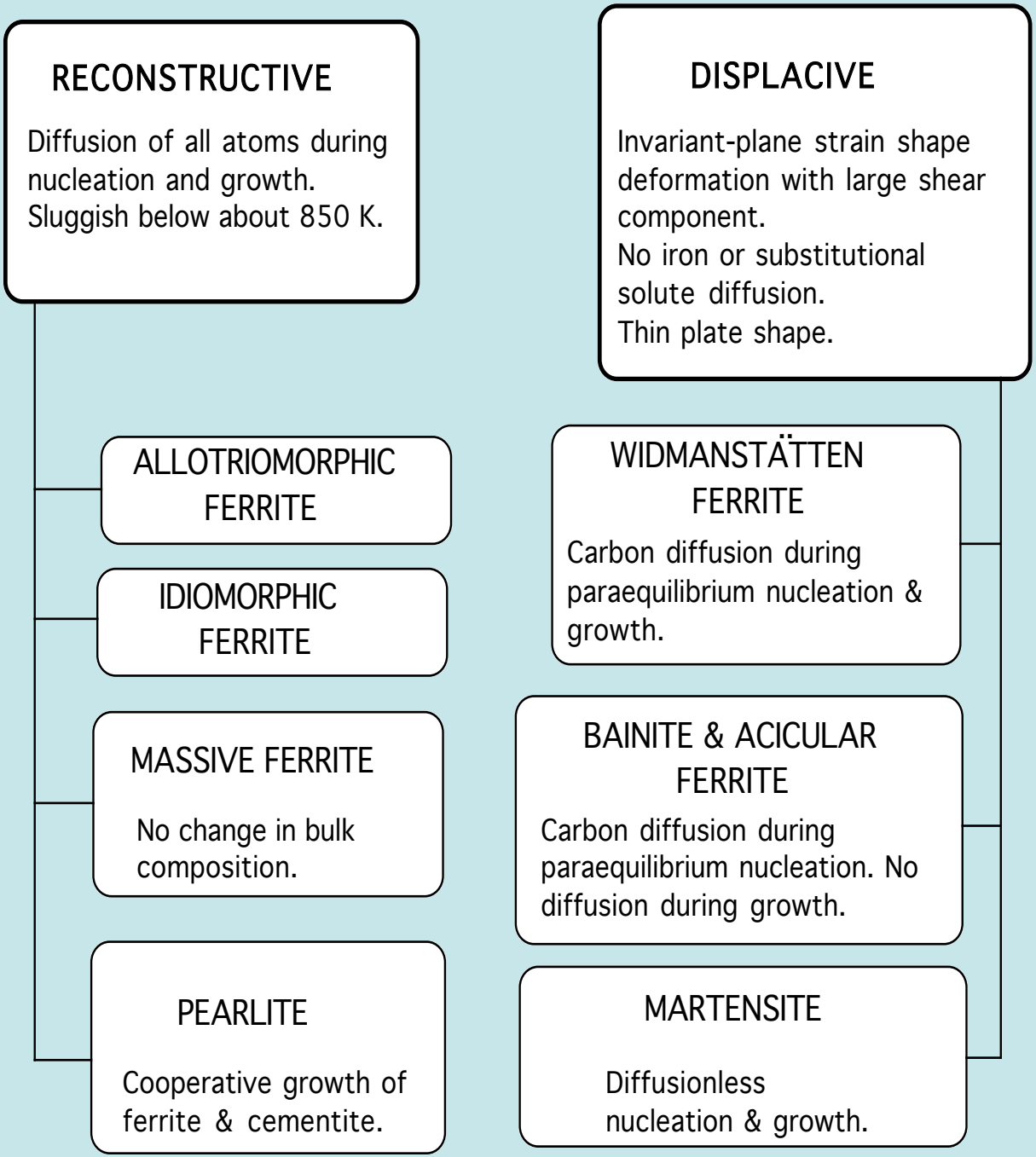
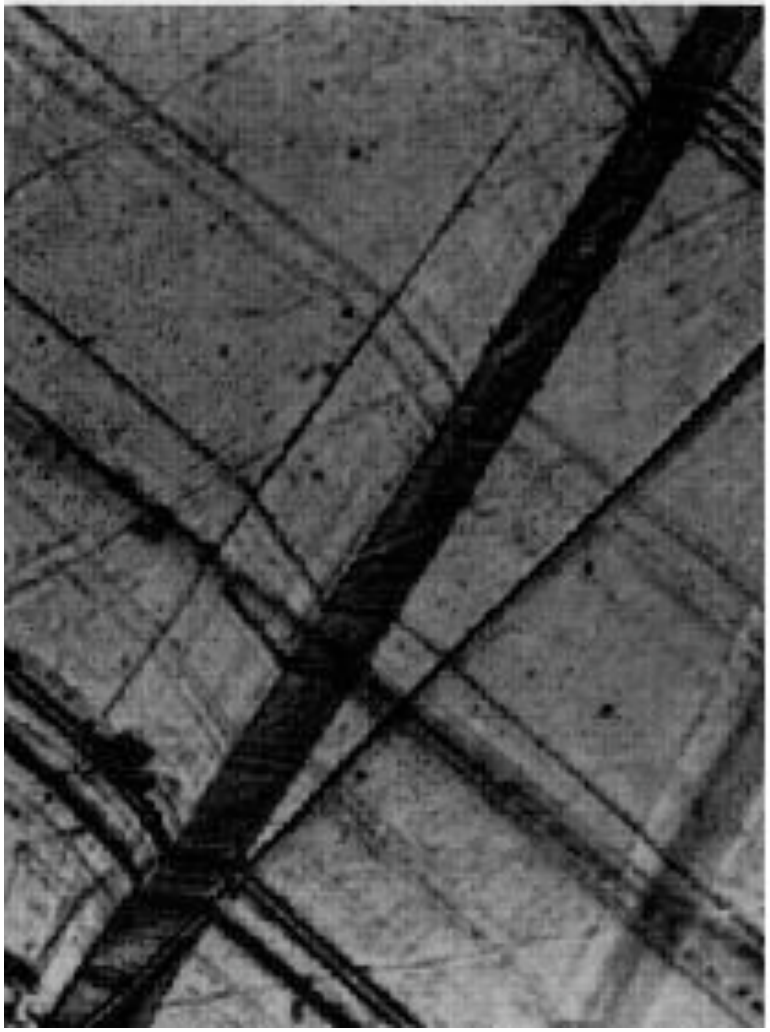
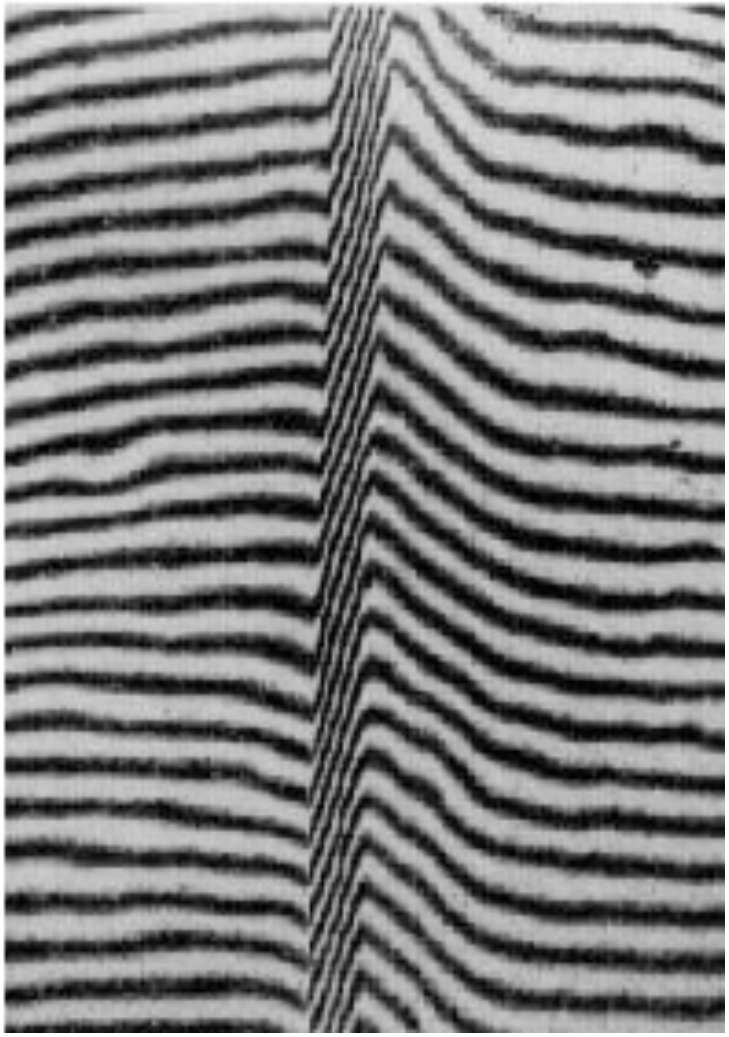
# Transformation Plasticity in Steel Welds

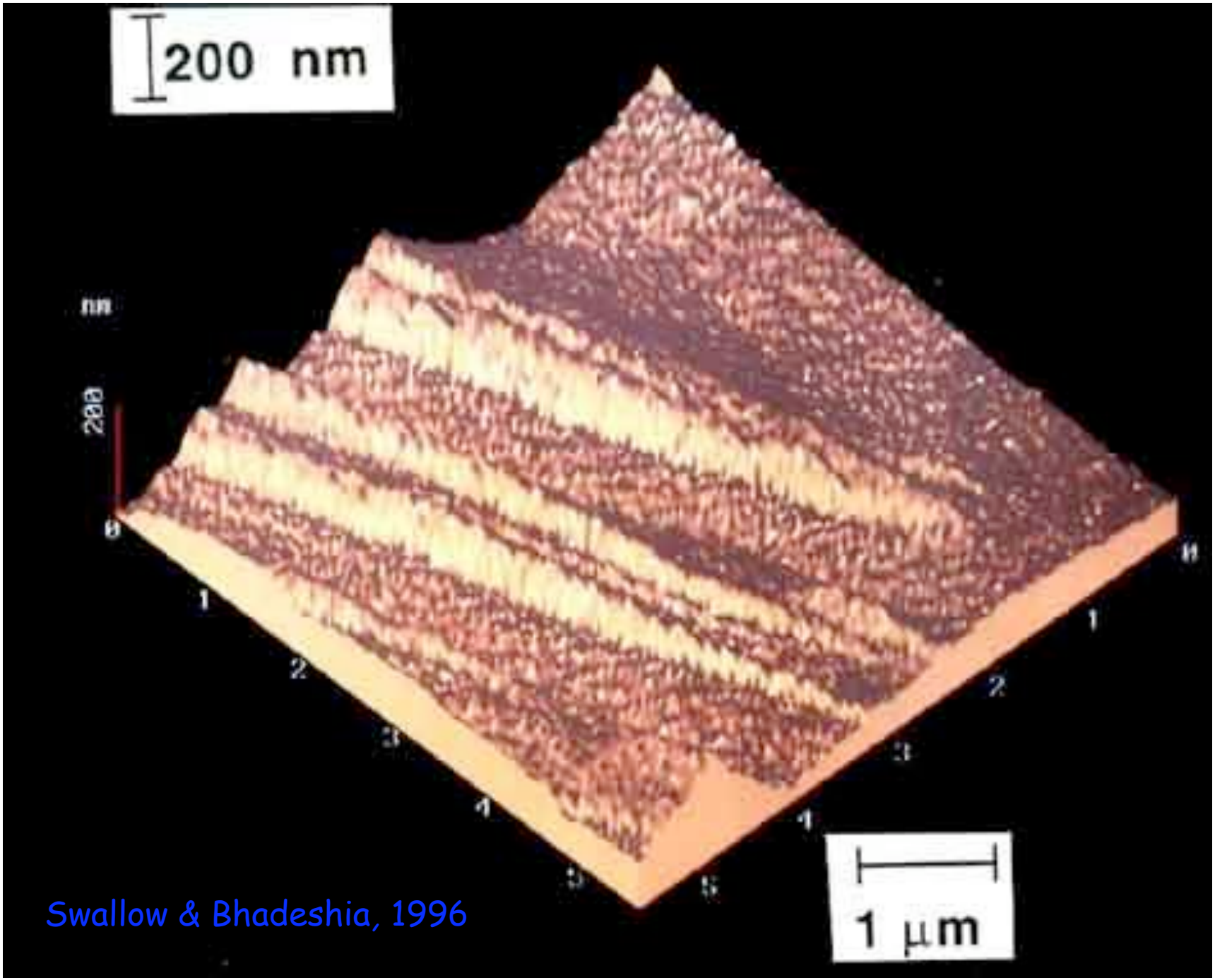



RECONSTRUCTIVE
Diffusion of all atoms during nucleation and growth.
Sluggish below about 850 K.
DISPLACIVE
Invariant-plane strain shape deformation with large shear component.
No iron or substitutional solute diffusion.
Thin plate shape.
ALLOTRIOMORPHIC FERRITE
IDIOMORPHIC FERRITE
MASSIVE FERRITE
No change in bulk composition.
PEARLITE
Cooperative growth of ferrite & cementite.
WIDMANSTÄTTEN FERRITE
Carbon diffusion during paraequilibrium nucleation & growth.
BAINITE & ACICULAR FERRITE
Carbon diffusion during paraequilibrium nucleation. No diffusion during growth.
MARTENSITE
Diffusionless nucleation & growth.

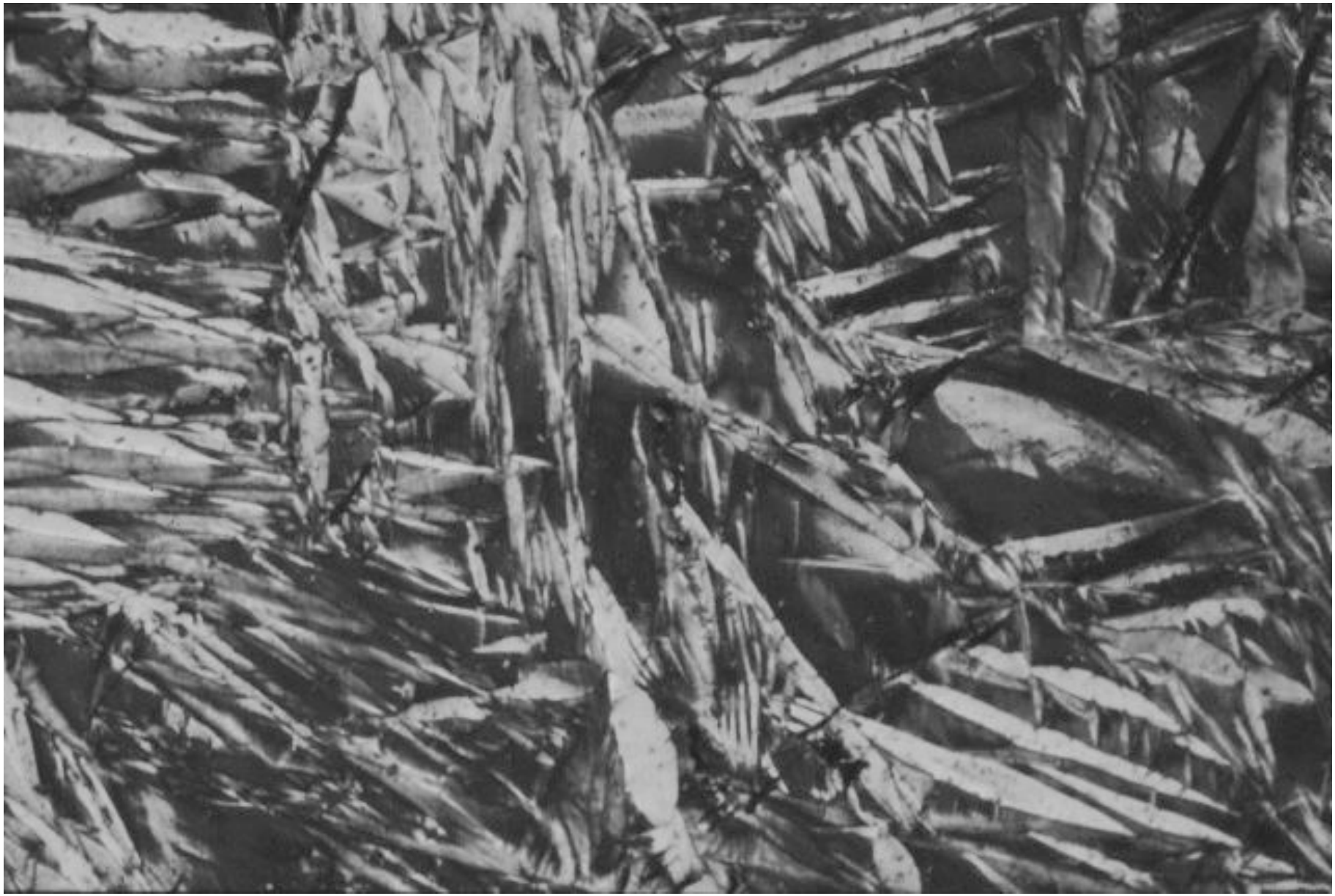


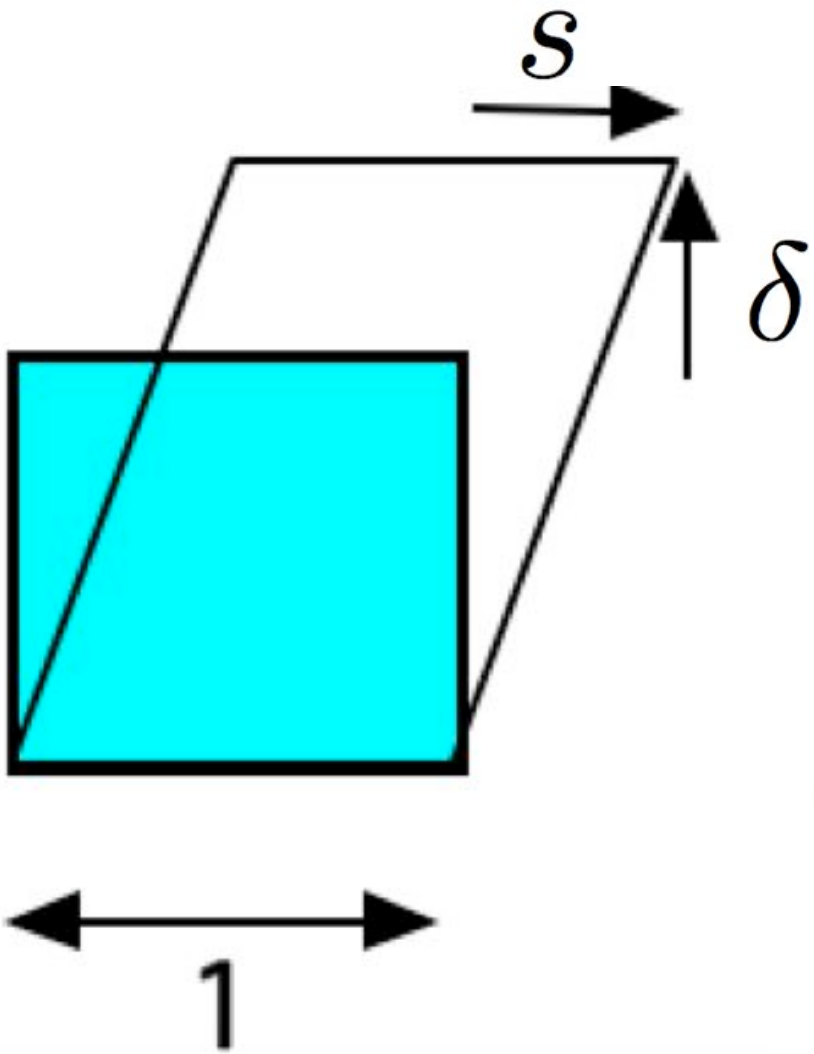


Watson and McDougall



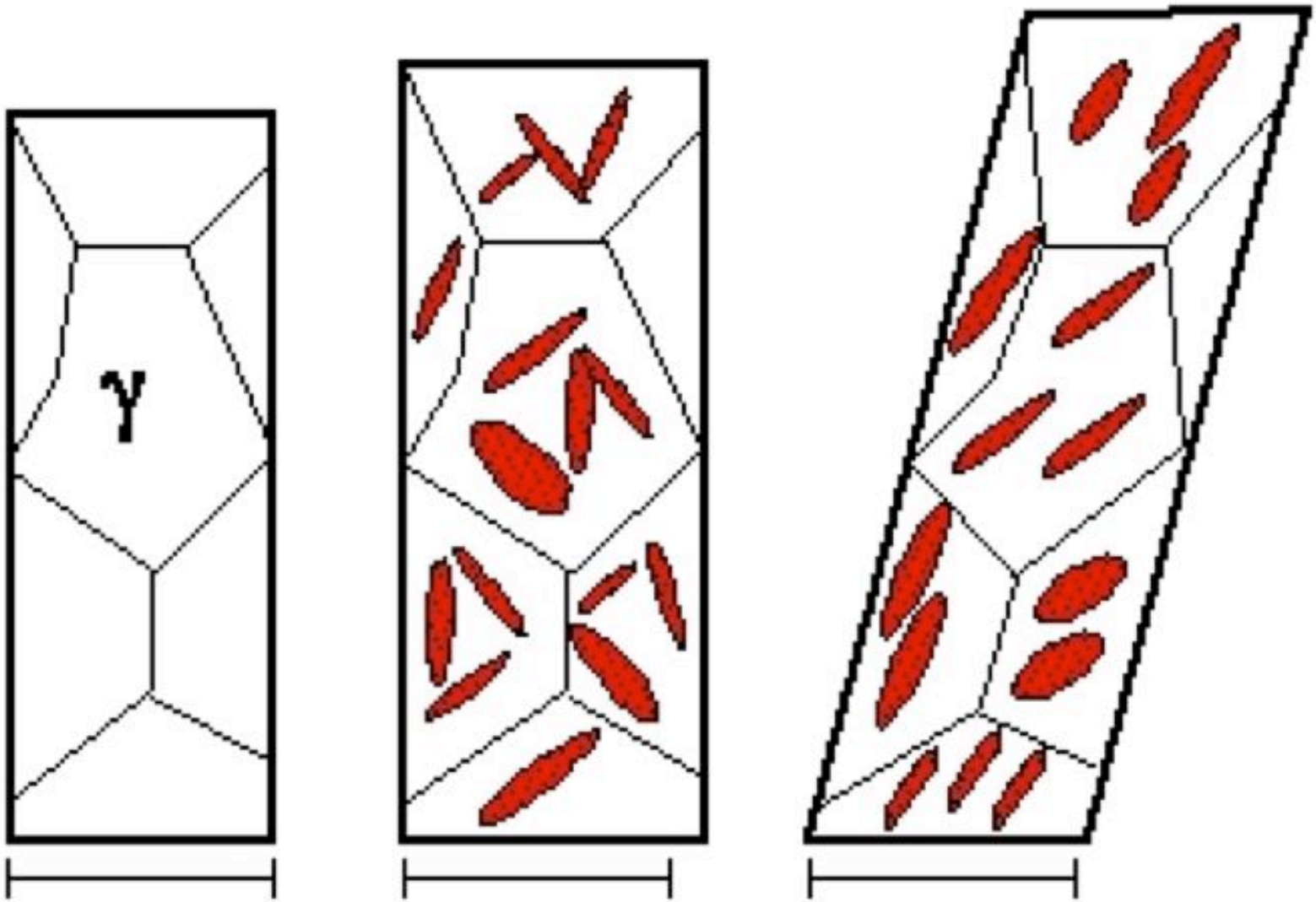

Swallow & Bhadeshia, 1996

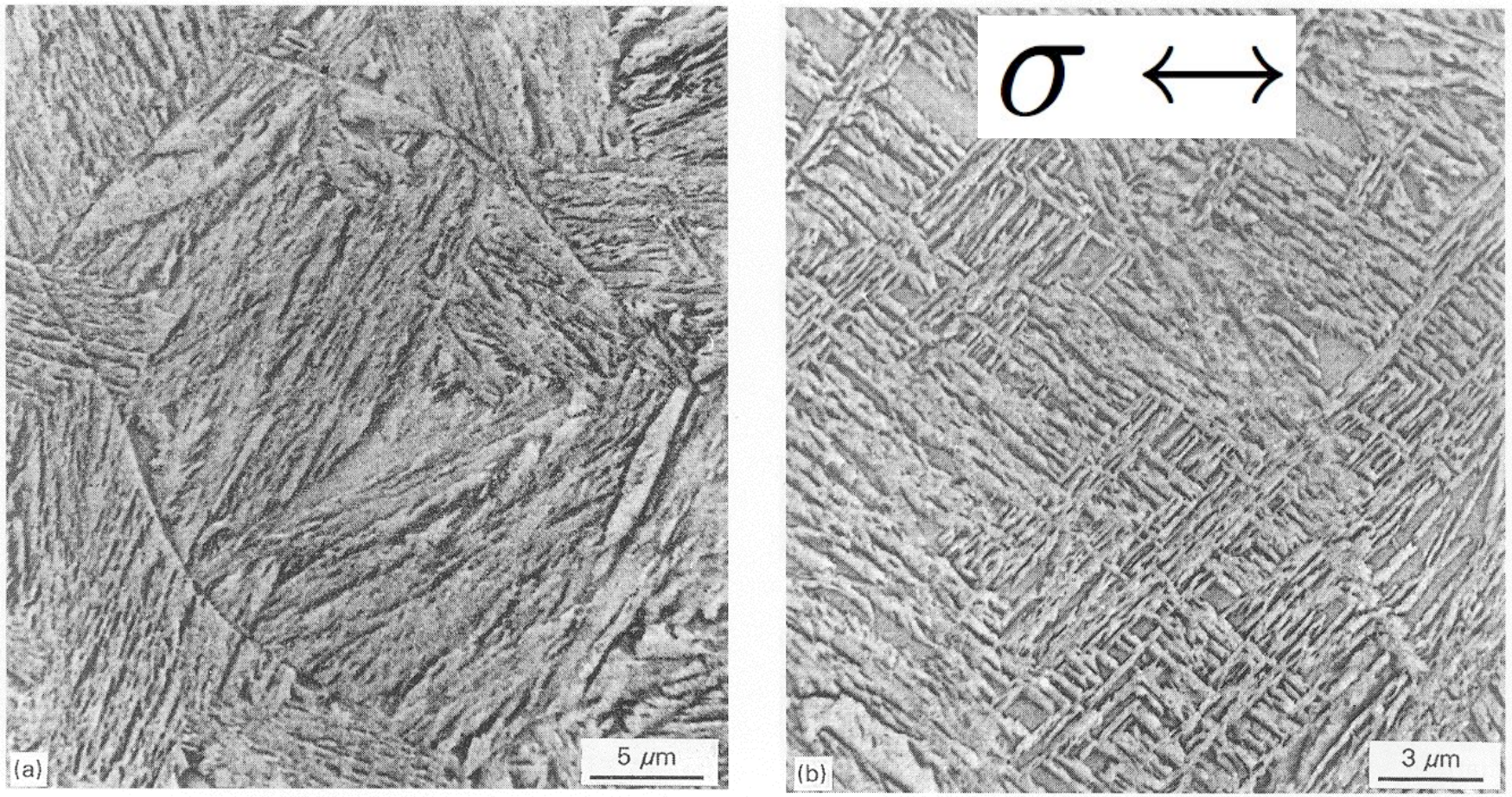





$$s = 0.26$$
$$\delta \simeq 0.03$$

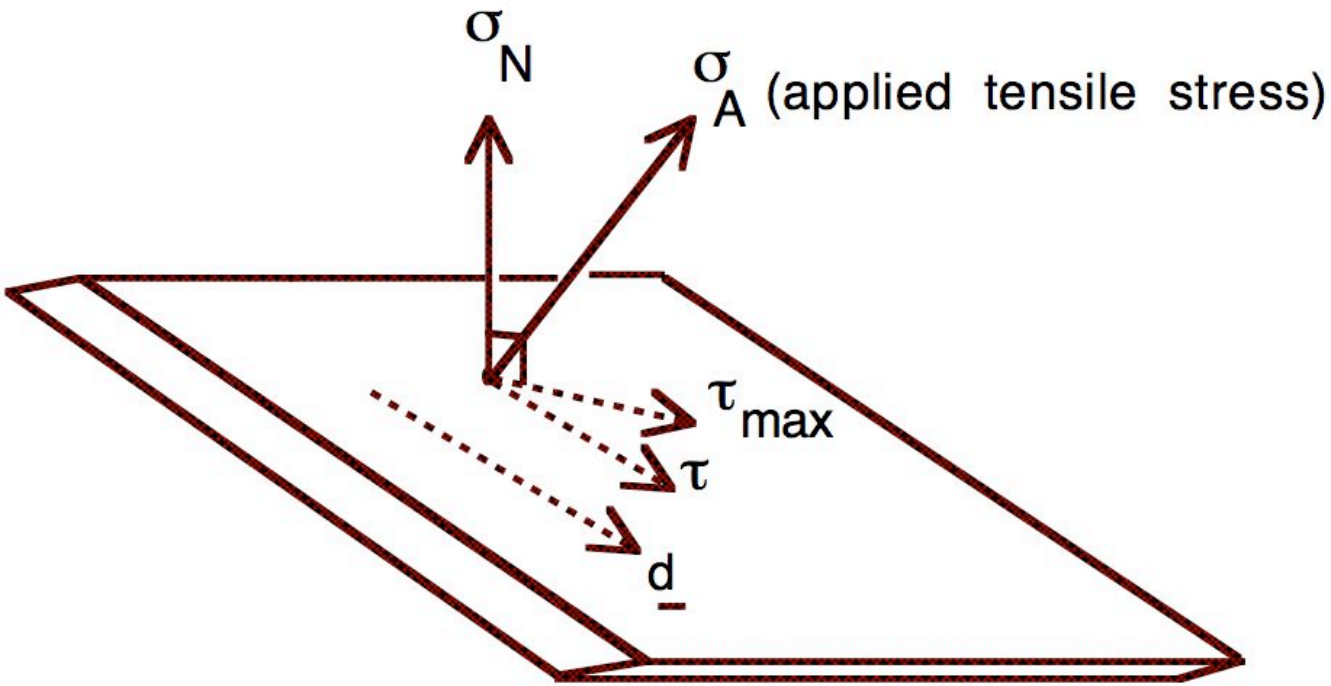
# possible elongation of 15%



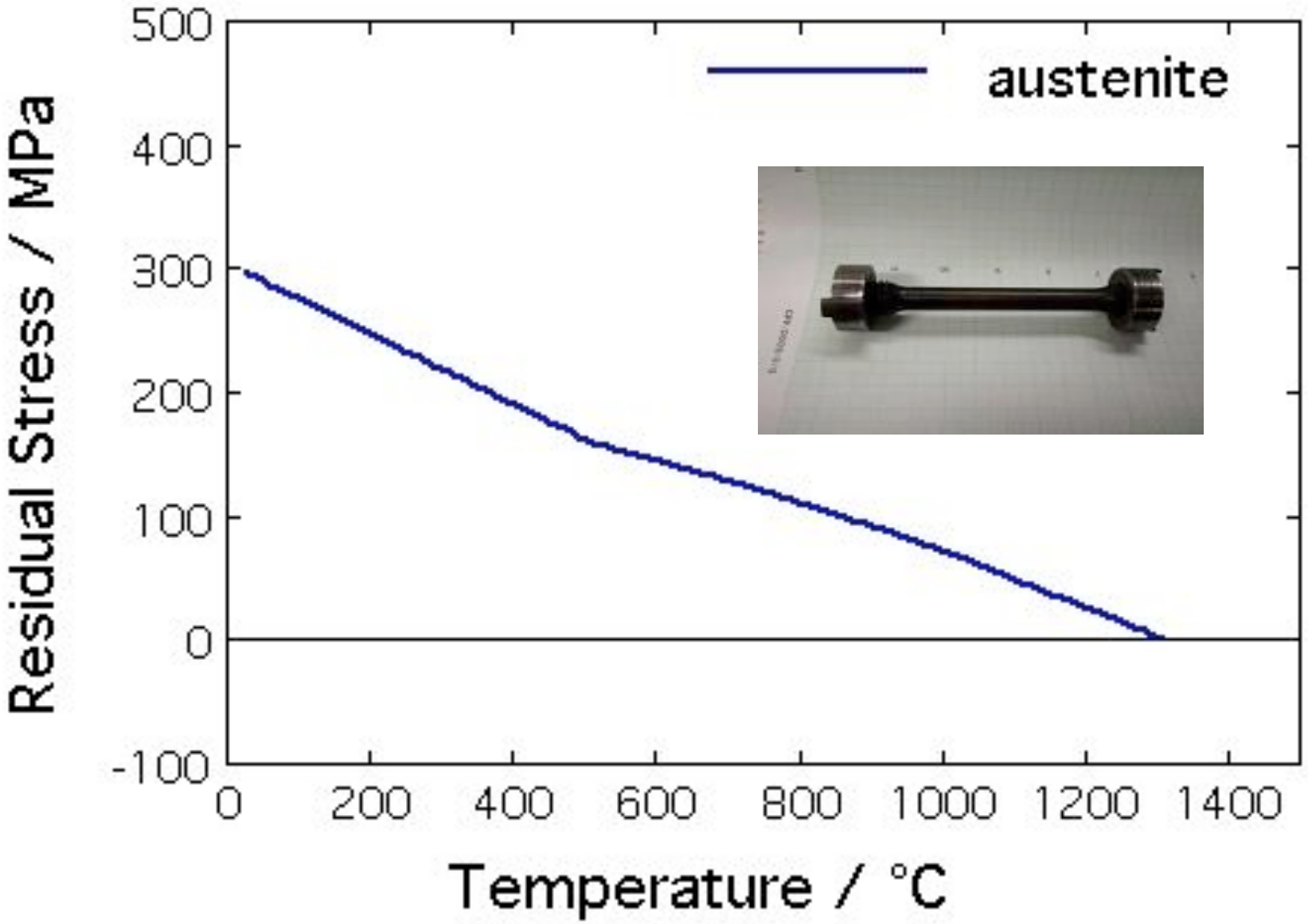


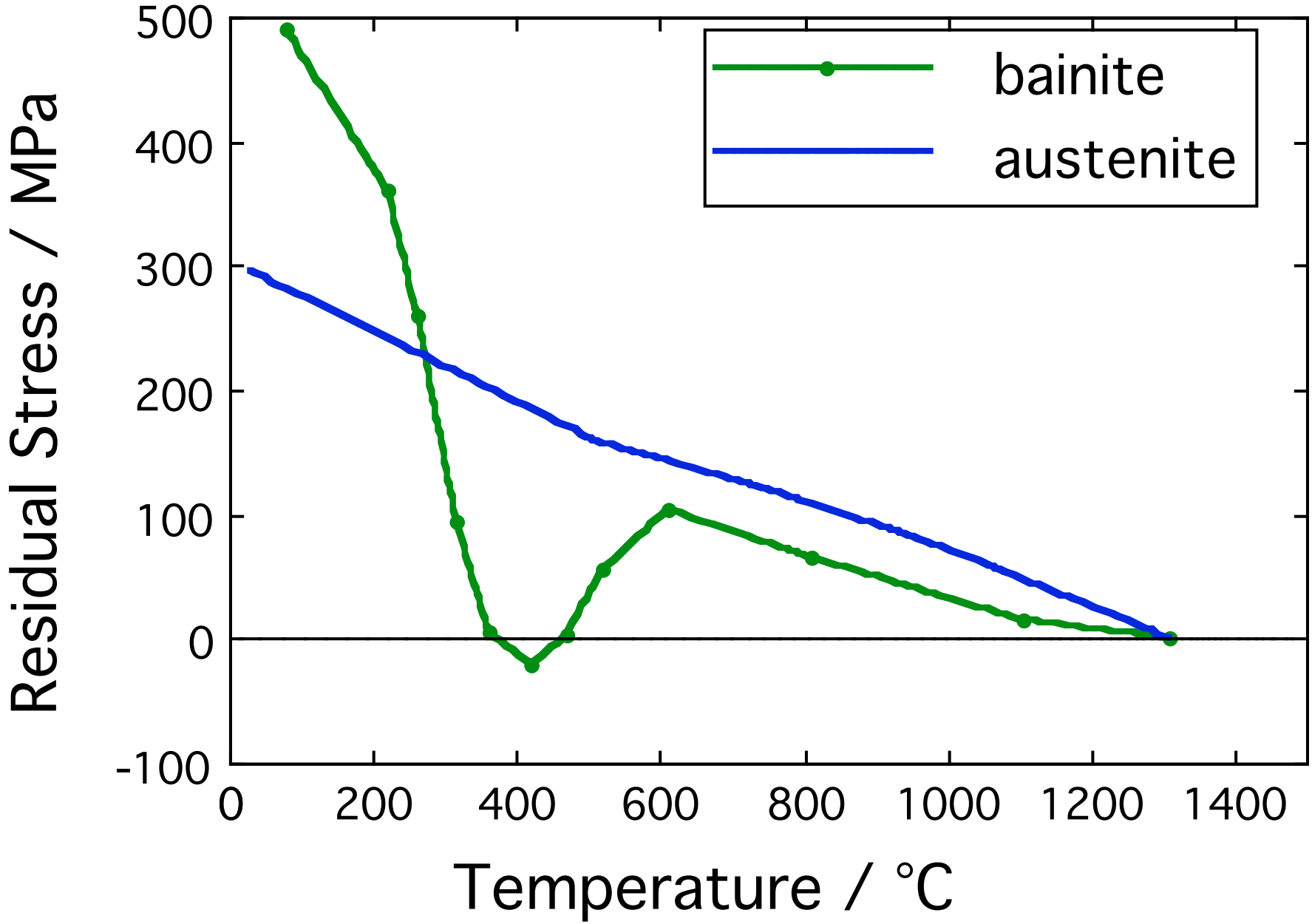

Lower bainite, transformed with and without stress

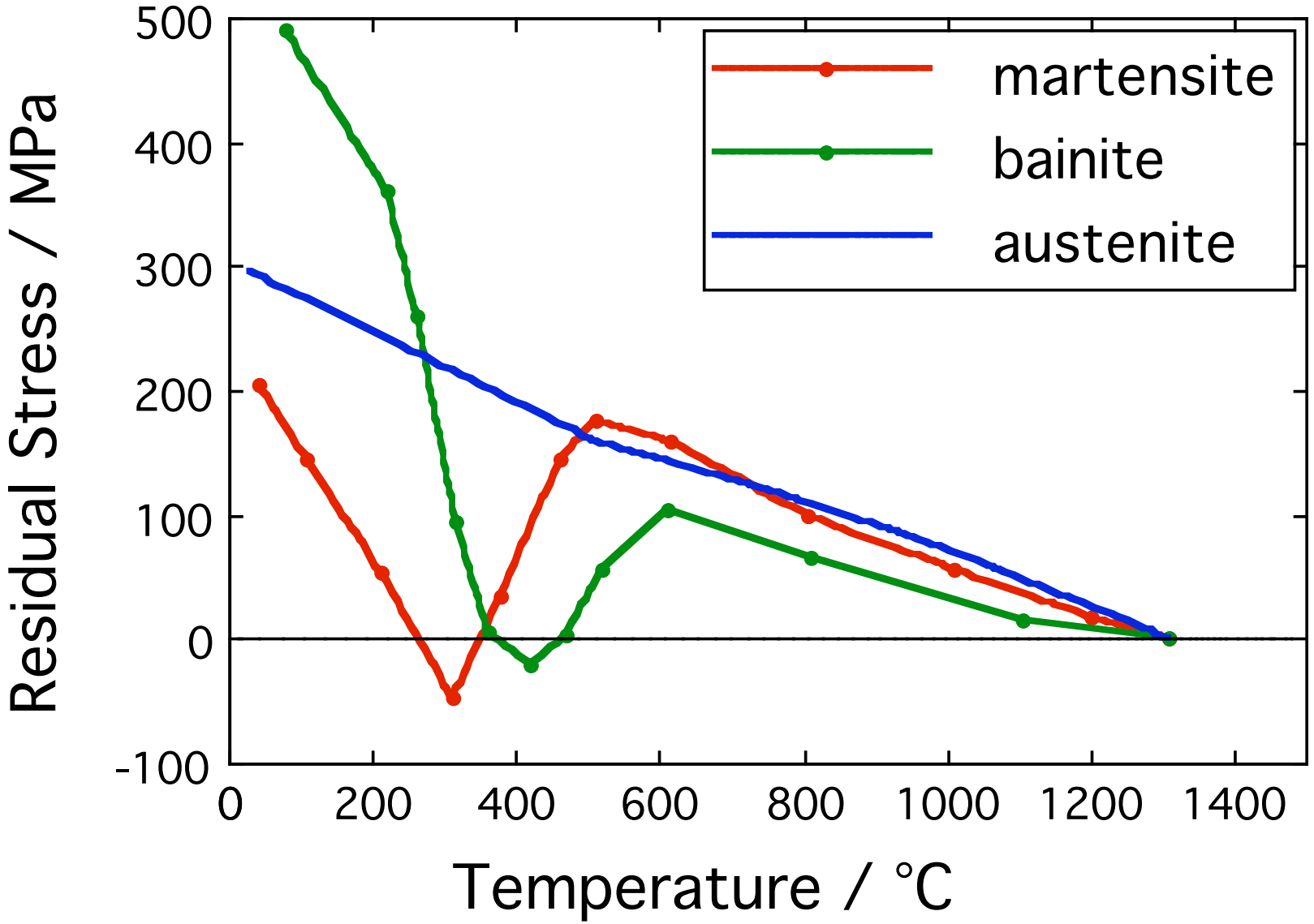
Chang et al., 1996



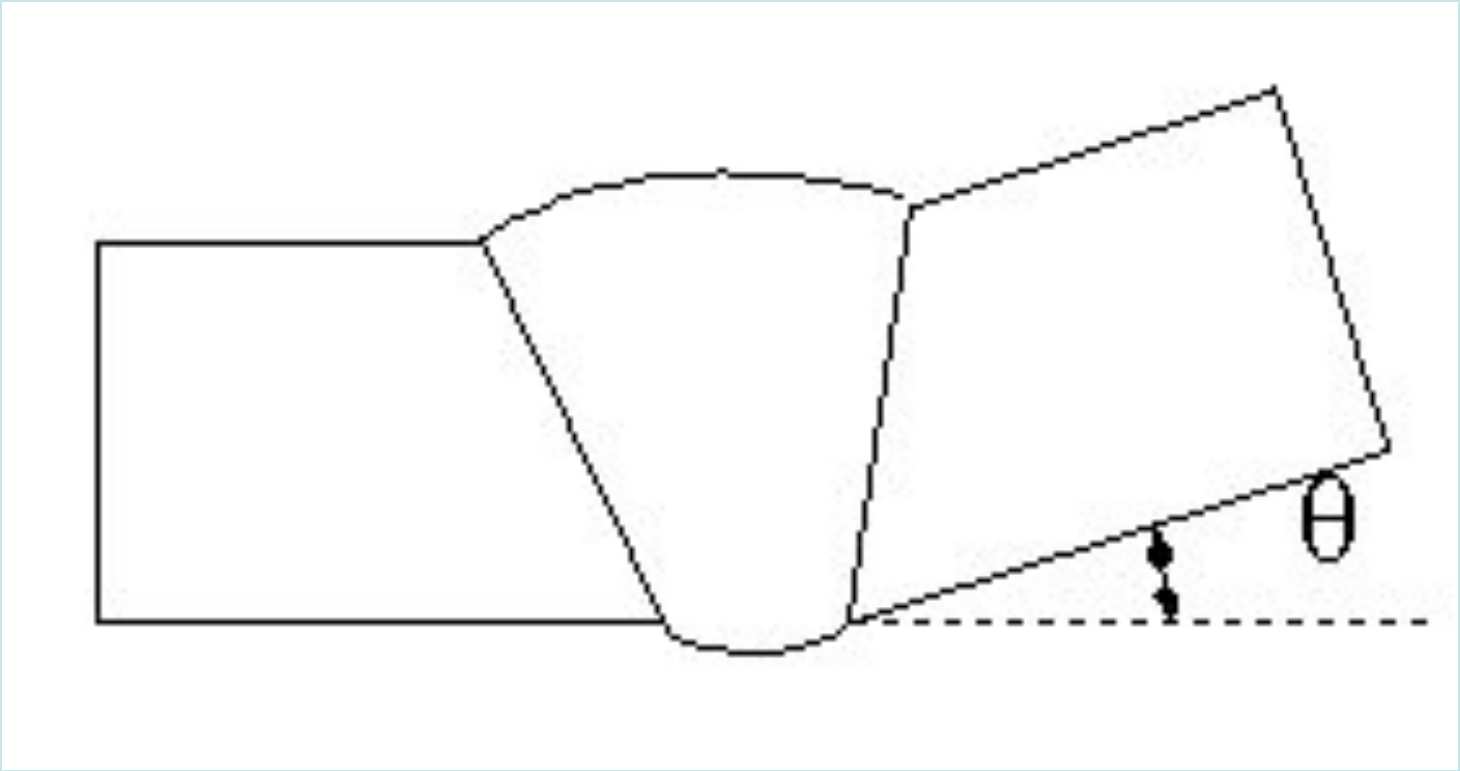

$$\Delta G_{MECH} = \tau s + \sigma_N \delta$$


Residual Stress / MPa
500
400
300
200
100
0
-100
0
200
400
600
800
1000
1200
1400
Temperature / °C
austenite


Residual Stress / MPa
500
400
300
200
100
0
-100
0
200
400
600
800
1000
1200
1400
Temperature / °C
bainite
austenite



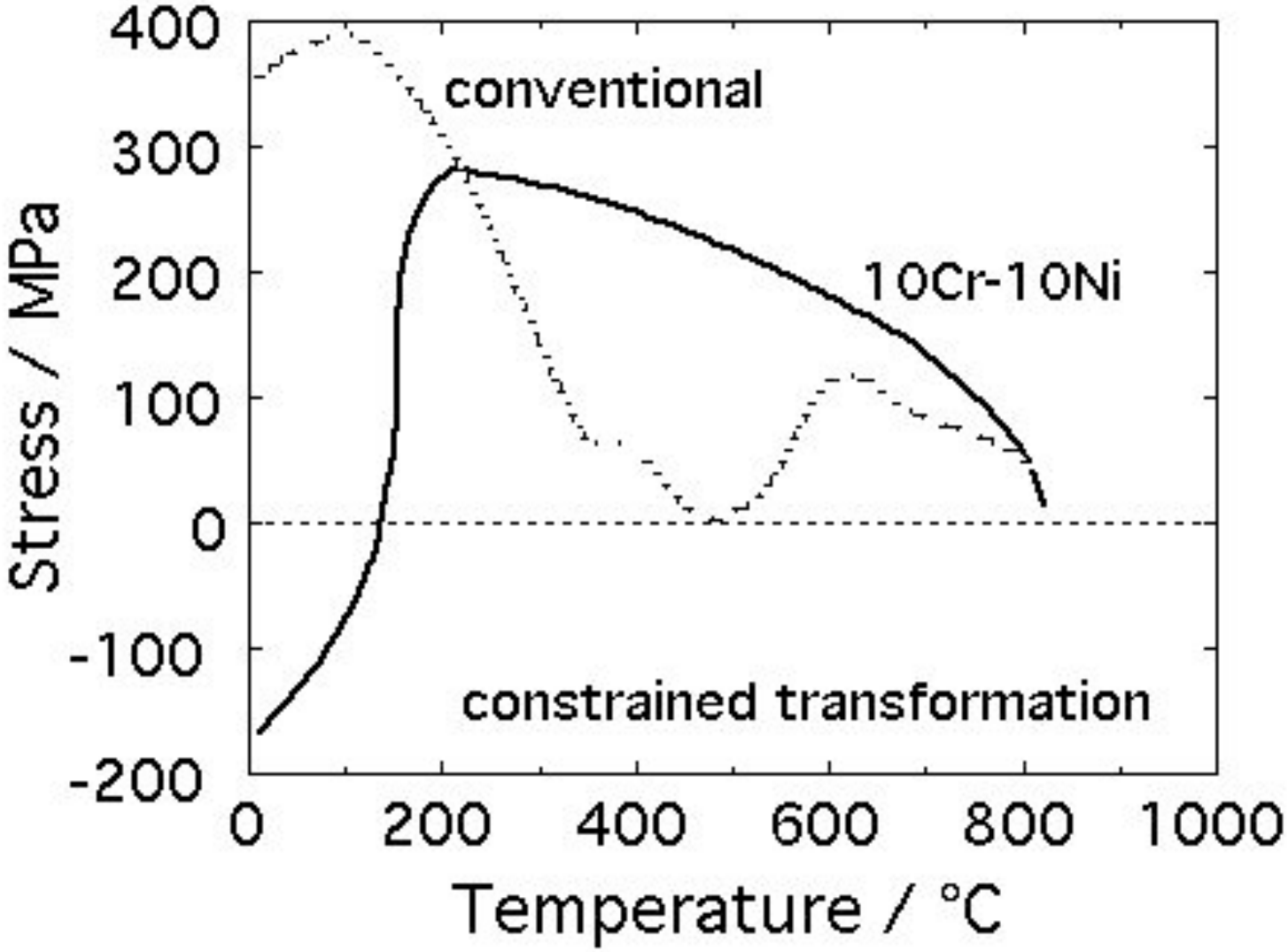

Jones & Alberry, 1977



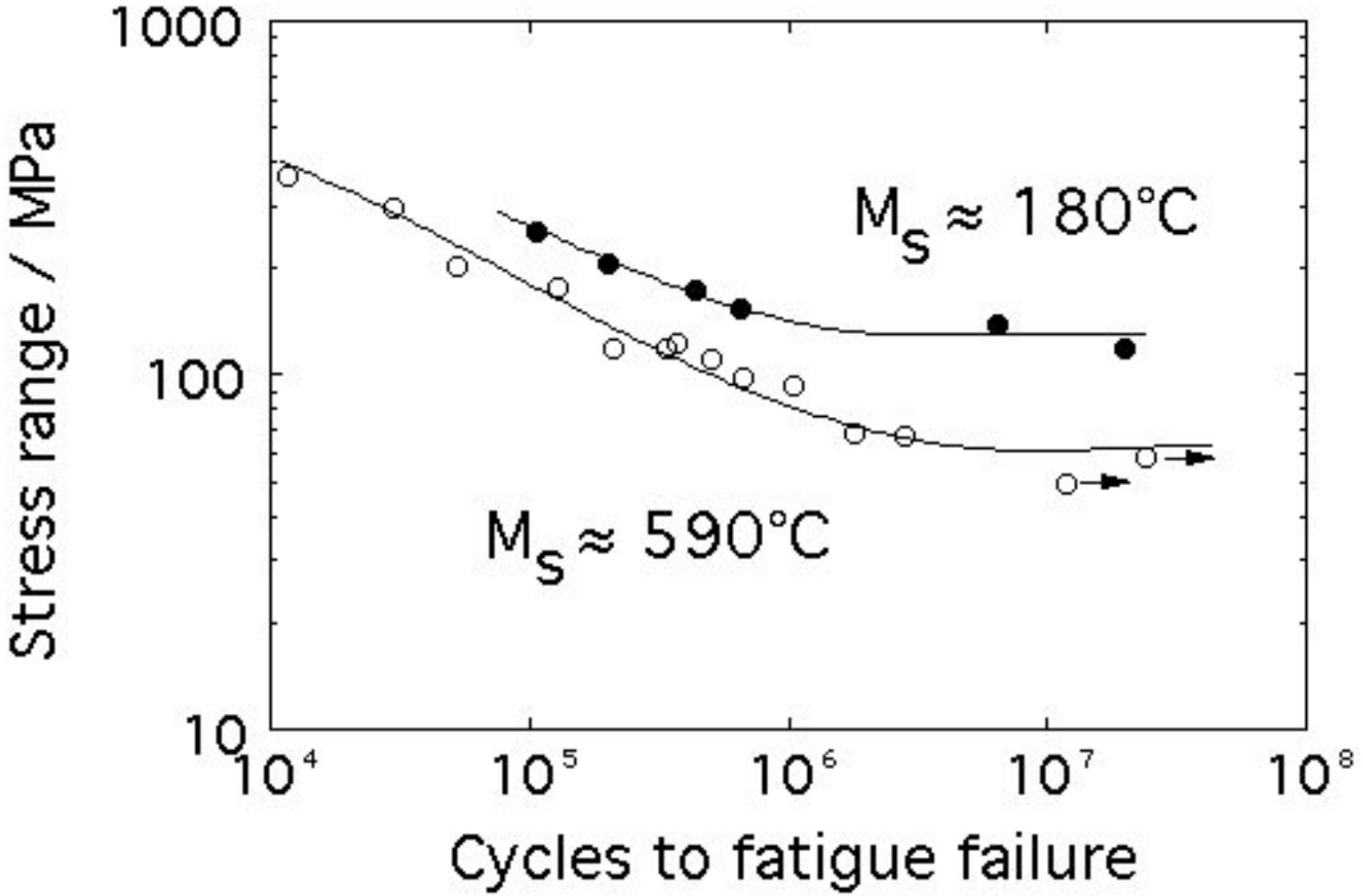

| C / wt.% | Si | Mn | Ni | Mo | Cr | $\Delta T$ / °C | $\theta$° |
|---|---|---|---|---|---|---|---|
| 0.06 | 0.5 | 0.9 | – | – | – | 802–400 | 14.5 |
| 0.06 | 0.3 | 1.6 | 1.7 | 0.4 | 0.35 | 422–350 | 8 |

| C / wt.% | Si | Mn | Ni | Mo | Cr | $M_S$ / °C |
|---|---|---|---|---|---|---|
| 0.10 | 0.39 | 0.90 | – | – | – | 590 |
| 0.025 | 0.32 | 0.70 | 10.0 | 0.13 | 10.0 | 180 |

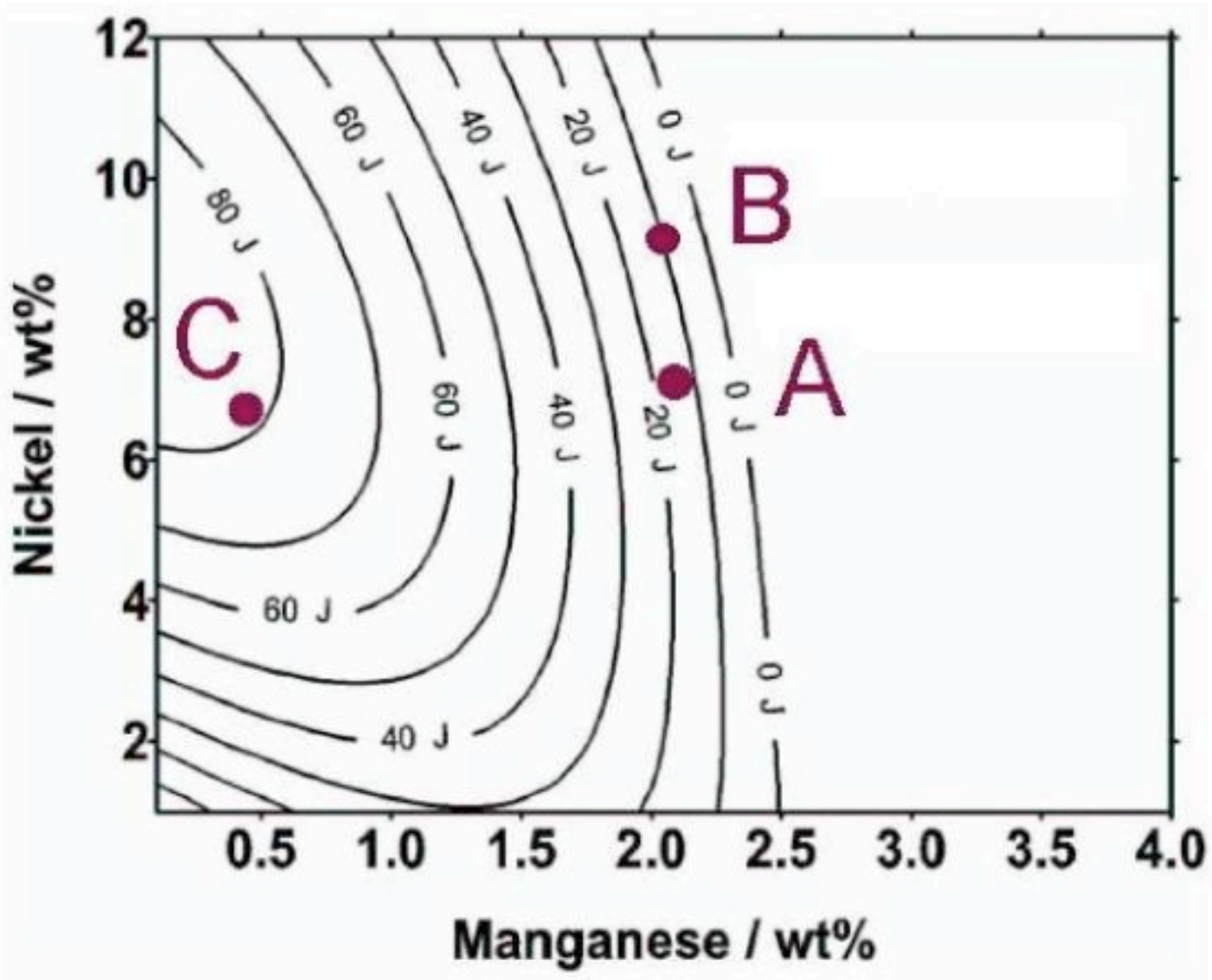
Ohta *et al.*, 2000-2003



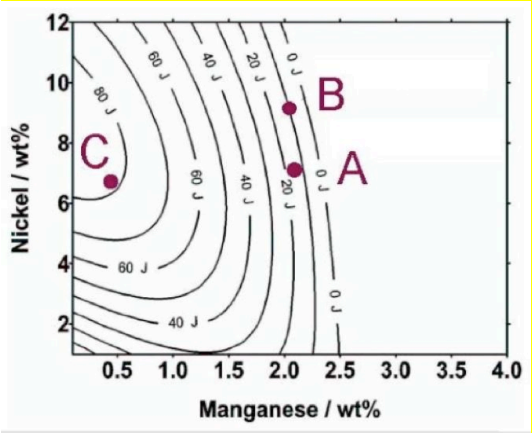

Ohta *et al.*, 2000-2003

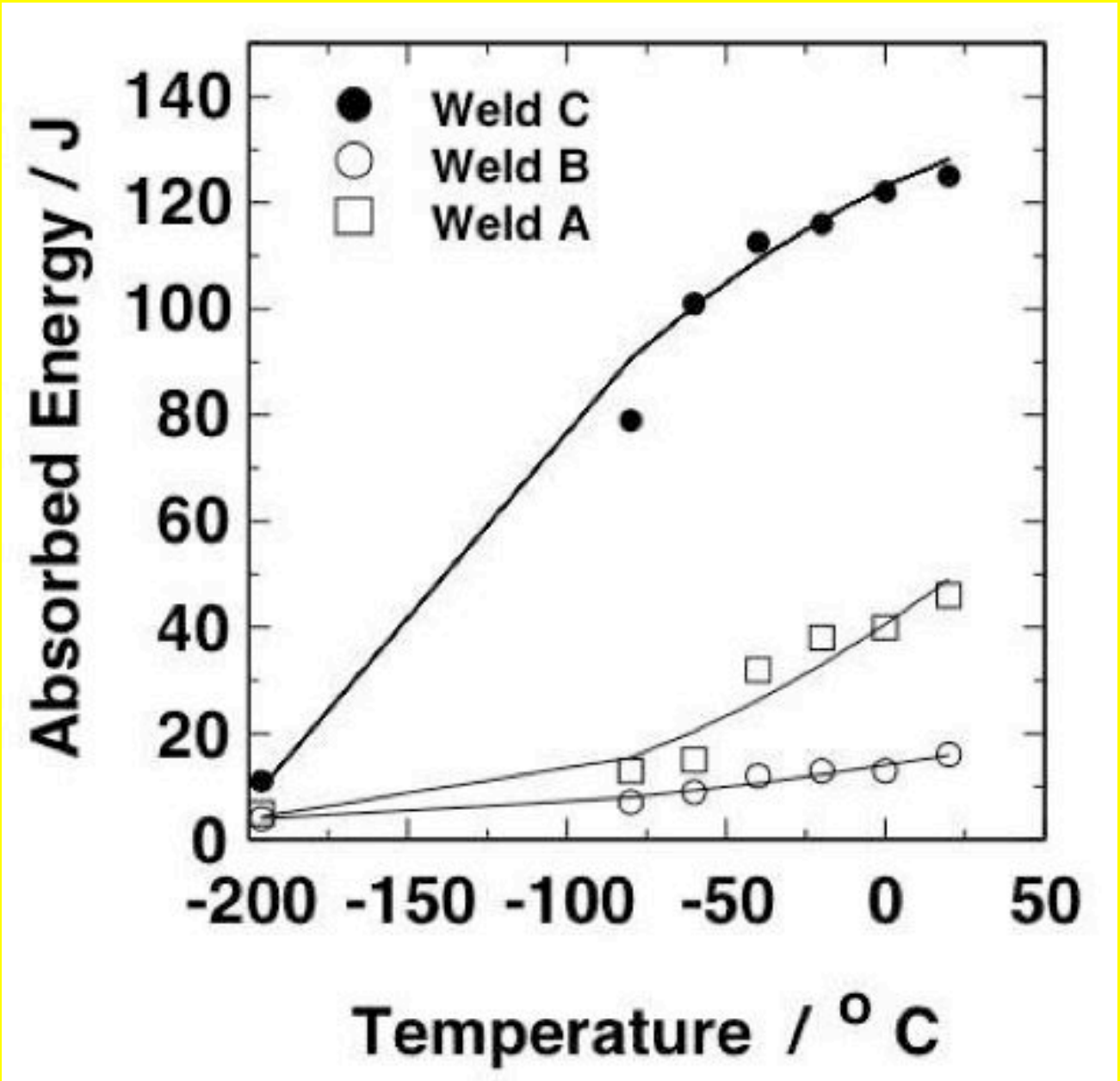


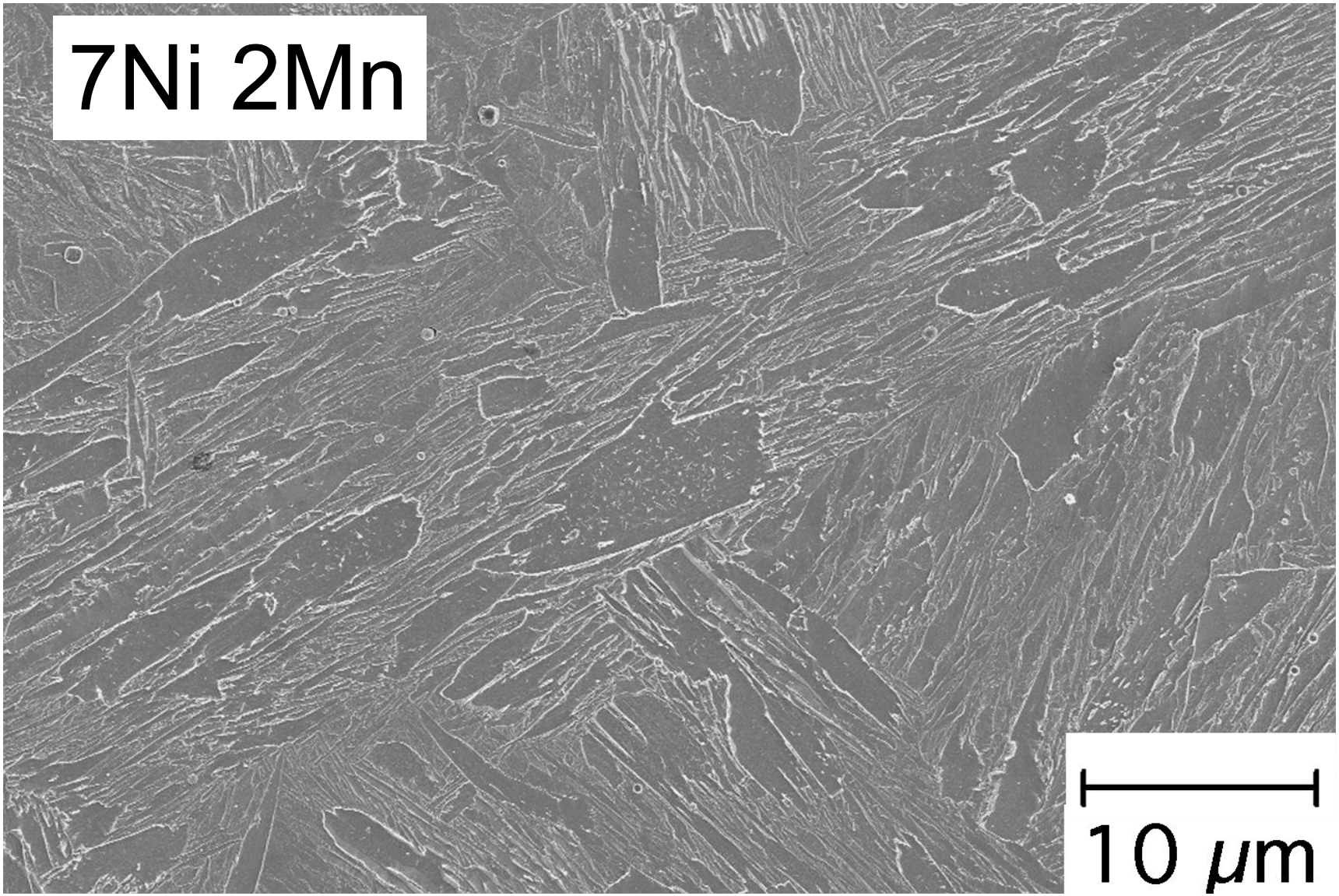

Ohta *et al.*, 2000-2003




Murugananth & Bhadeshia


Nickel / wt%
Manganese / wt%
12
10
8
6
4
2
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
80 J
60 J
40 J
20 J
0 J
B
C
A

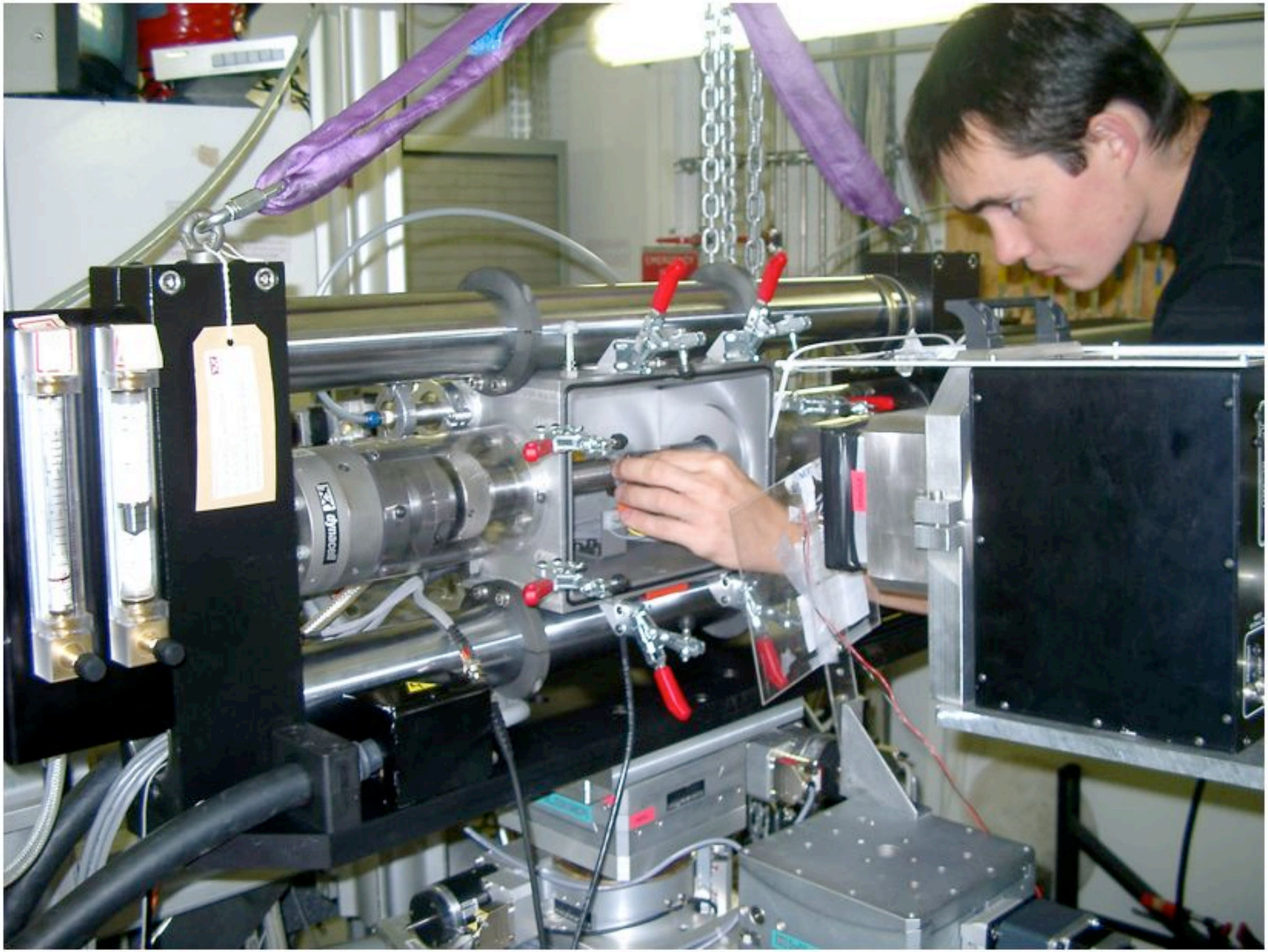

Absorbed Energy / J
Temperature / °C
Weld C
Weld B
Weld A
140
120
100
80
60
40
20
0
-200
-150
-100
-50
0
50

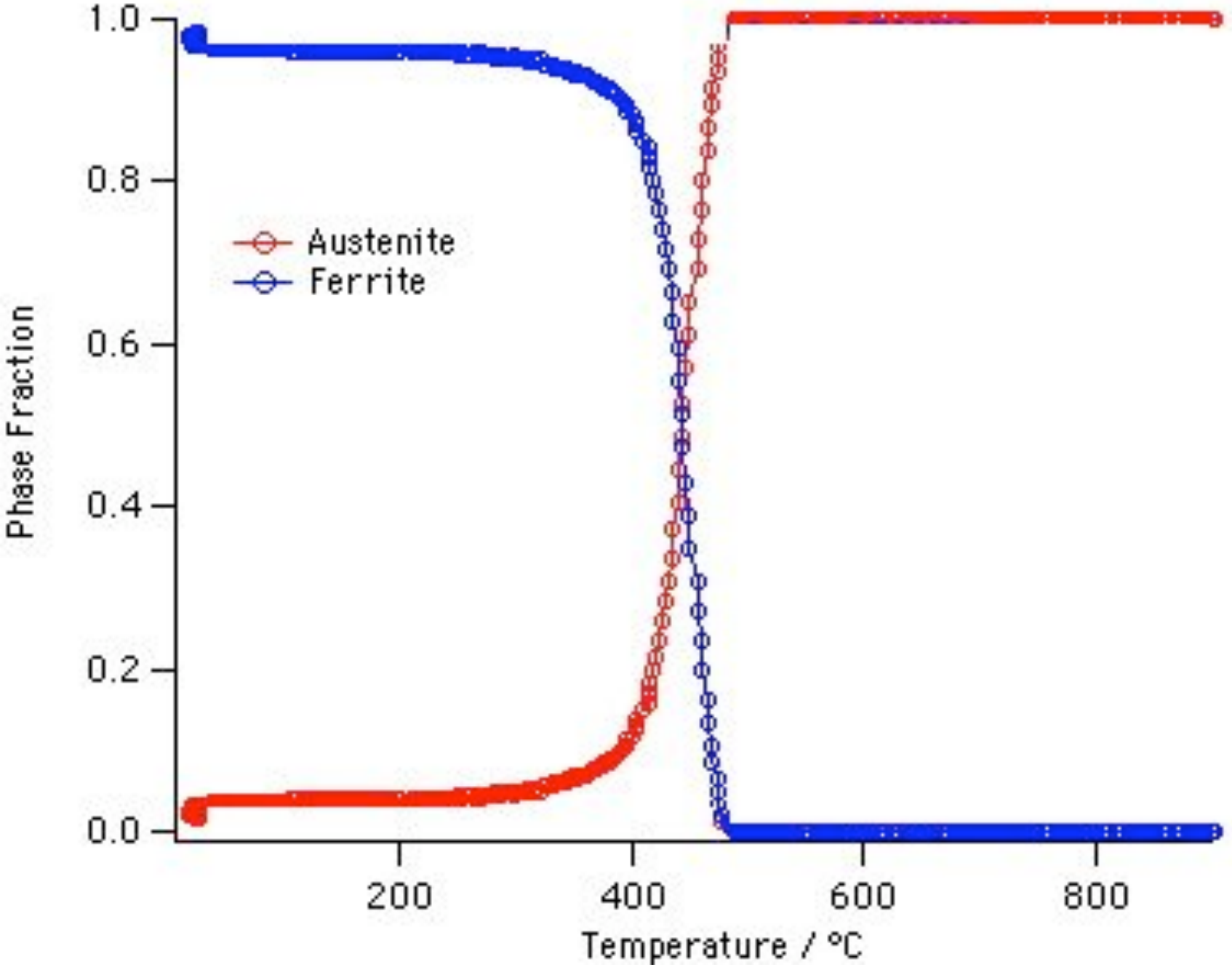


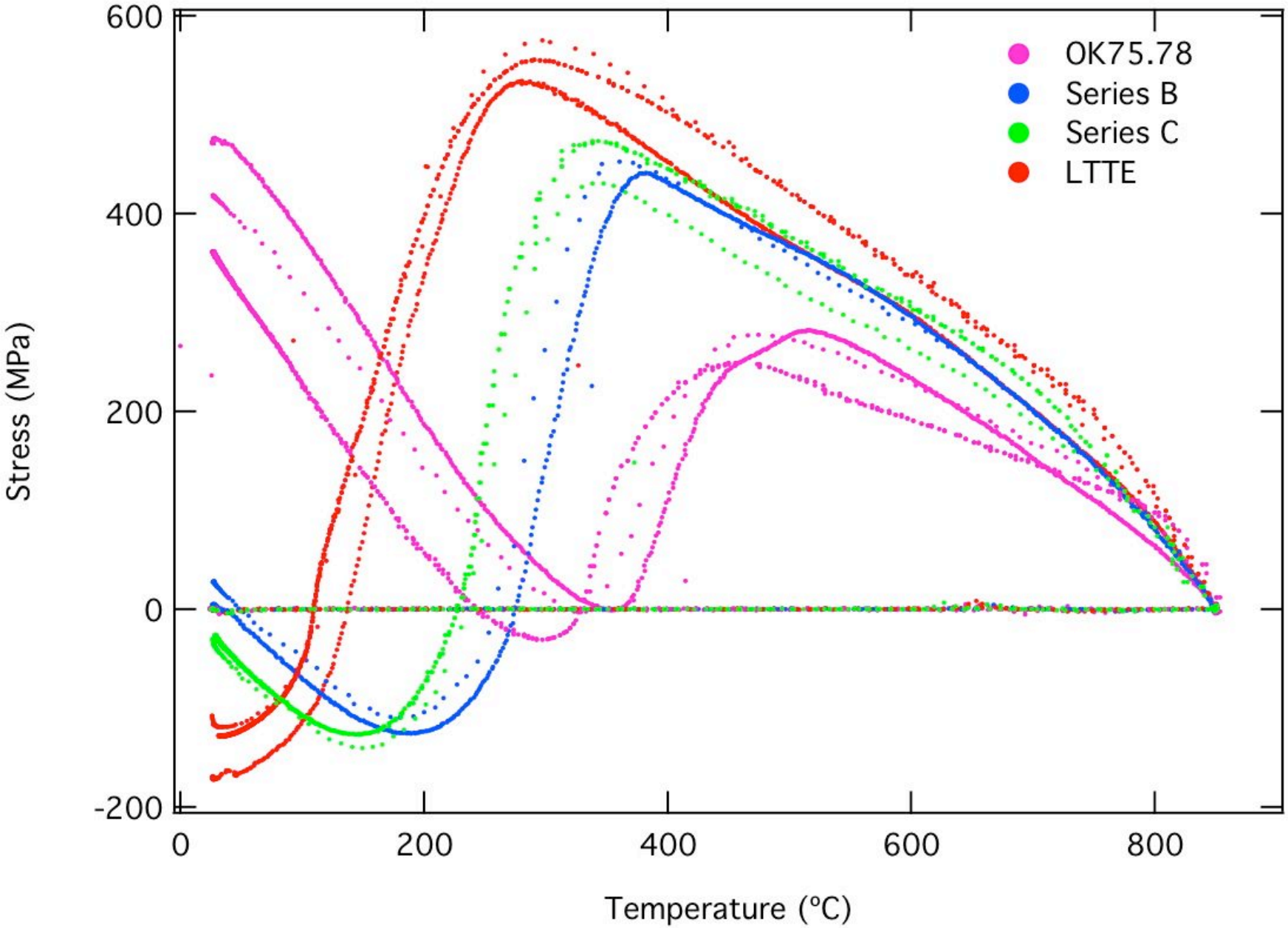

Keehan, Karlsson, Andrén, Bhadeshia,

Science & Techn. Welding & Joining 11 (2006) 9-18

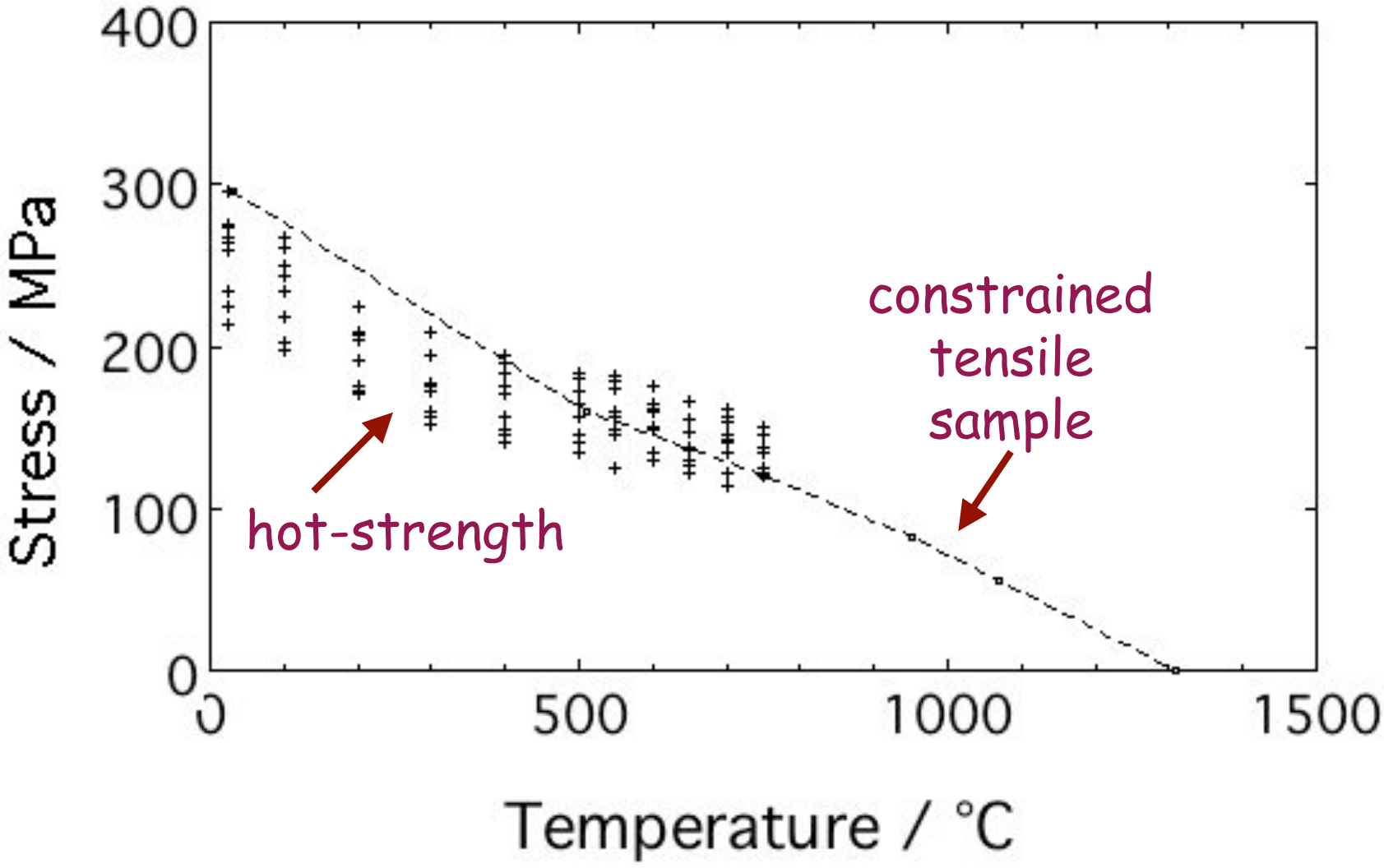
| Alloy | C | Si | Mn | Cr | Ni | Mo |
|---|---|---|---|---|---|---|
| OK 75.78 | 0.05 | 0.19 | 2.01 | 0.41 | 3.14 | 0.63 |
| B | 0.03 | 0.65 | 0.5 | 1 | 12 | 0.5 |
| C | 0.045 | 0.4 | 0.5 | 0.4 | 14 | 0.4 |
| LTTE3 | 0.07 | 0.2 | 1.25 | 9.1 | 8.5 | |




1.0
0.8
0.6
0.4
0.2
0.0
Phase Fraction
Austenite
Ferrite
200
400
600
800
Temperature / °C


600
400
200
0
-200
0
200
400
600
800
Stress (MPa)
Temperature (°C)
OK75.78
Series B
Series C
LTTE

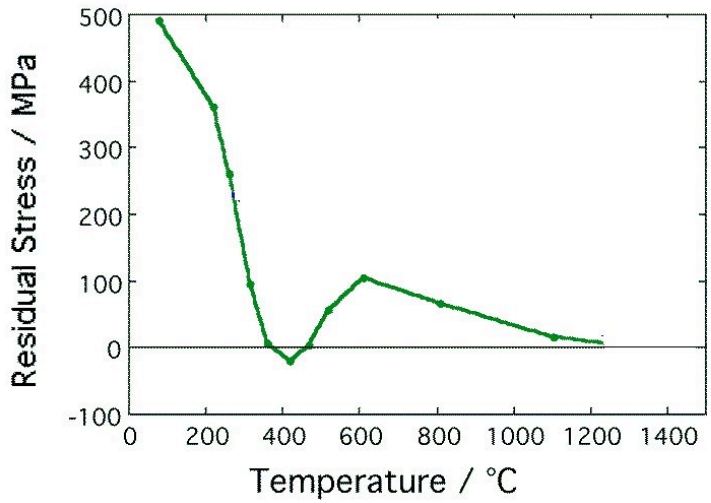
316 austenitic stainless steel



Transformation strain

24 variants of martensite per austenite grain

Variant selection



## Habit plane $\mathbf{p}_\gamma$

$$\begin{pmatrix} -0.168640 \\ -0.760394 \\ -0.627185 \end{pmatrix}$$

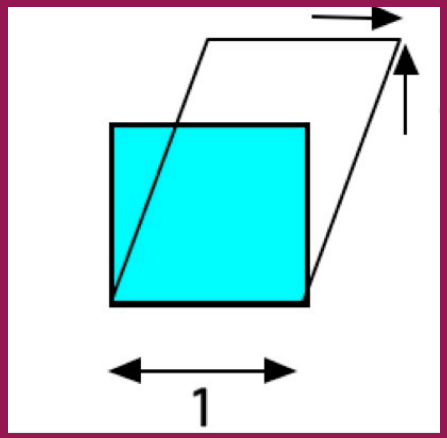
## Orientation ($\gamma$ J $\alpha$)

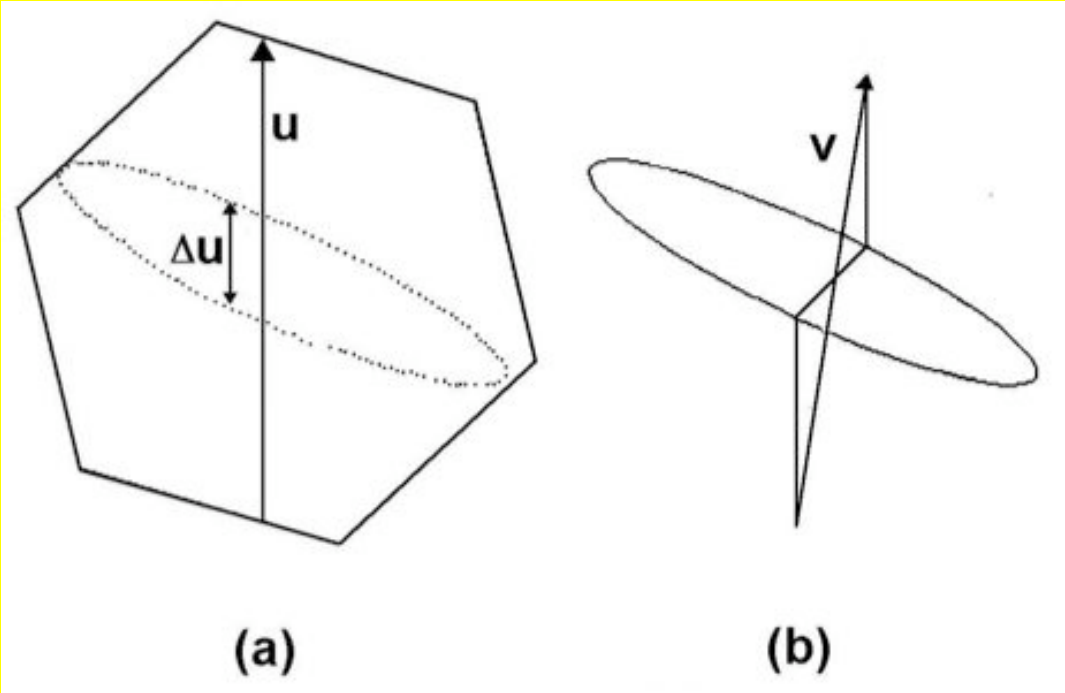
$$\begin{pmatrix} 0.575191 & 0.542067 & 0.097283 \\ -0.550660 & 0.568276 & 0.089338 \\ -0.008610 & -0.131800 & 0.785302 \end{pmatrix}$$

$$[\bar{1}\ 0\ 1]_\gamma || [-0.920611\ -1.062637\ 1.084959]_{\alpha'}$$
$$(1\ 1\ 1)_\gamma || (0.015921\ 0.978543\ 0.971923)_{\alpha'}$$

## Shape change ($\gamma$ P $\gamma$)

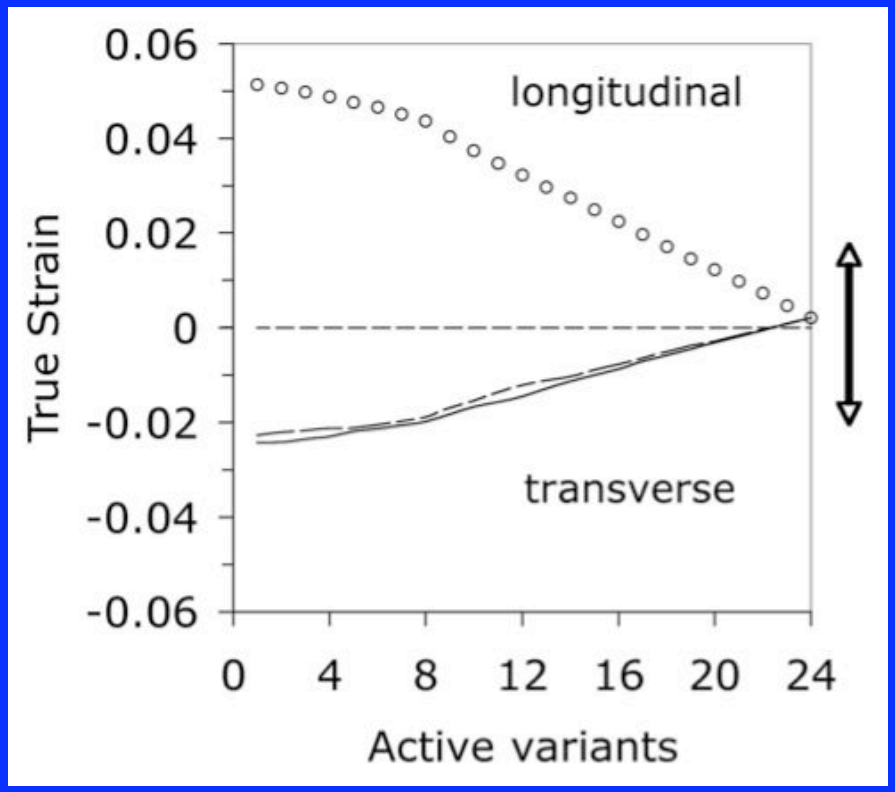
$$\begin{pmatrix} 0.992654 & -0.033124 & -0.027321 \\ 0.026378 & 1.118936 & 0.098100 \\ -0.027321 & -0.123190 & 0.898391 \end{pmatrix}$$

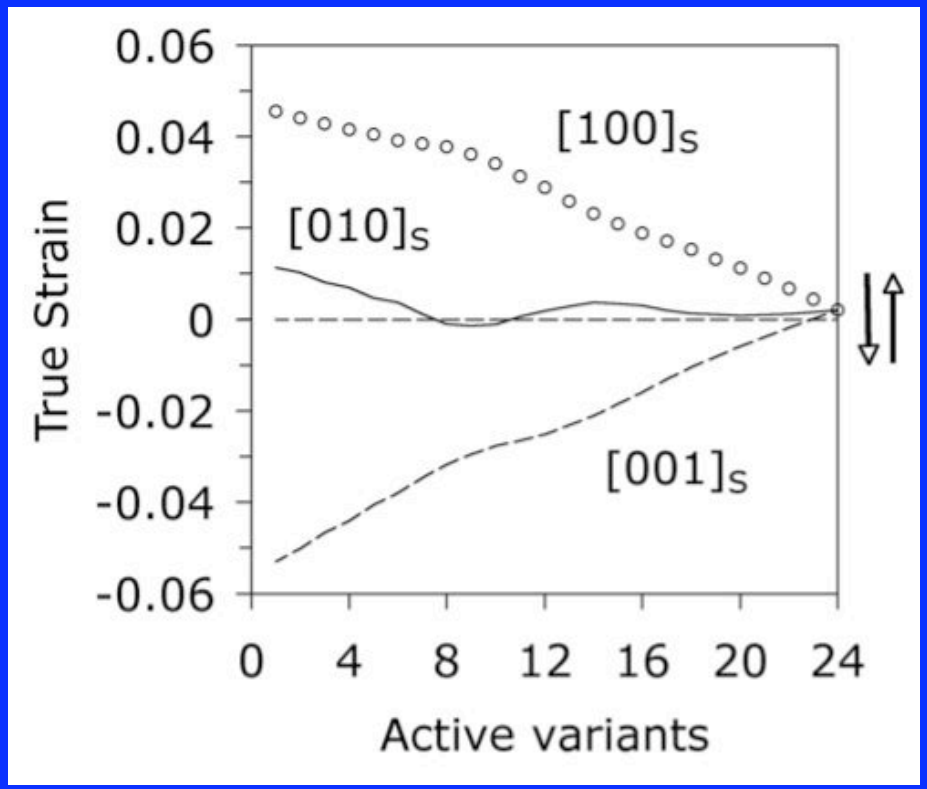





$$\mathbf{v} = \mathbf{P}\Delta\mathbf{u} + (\mathbf{u} - \Delta\mathbf{u})$$

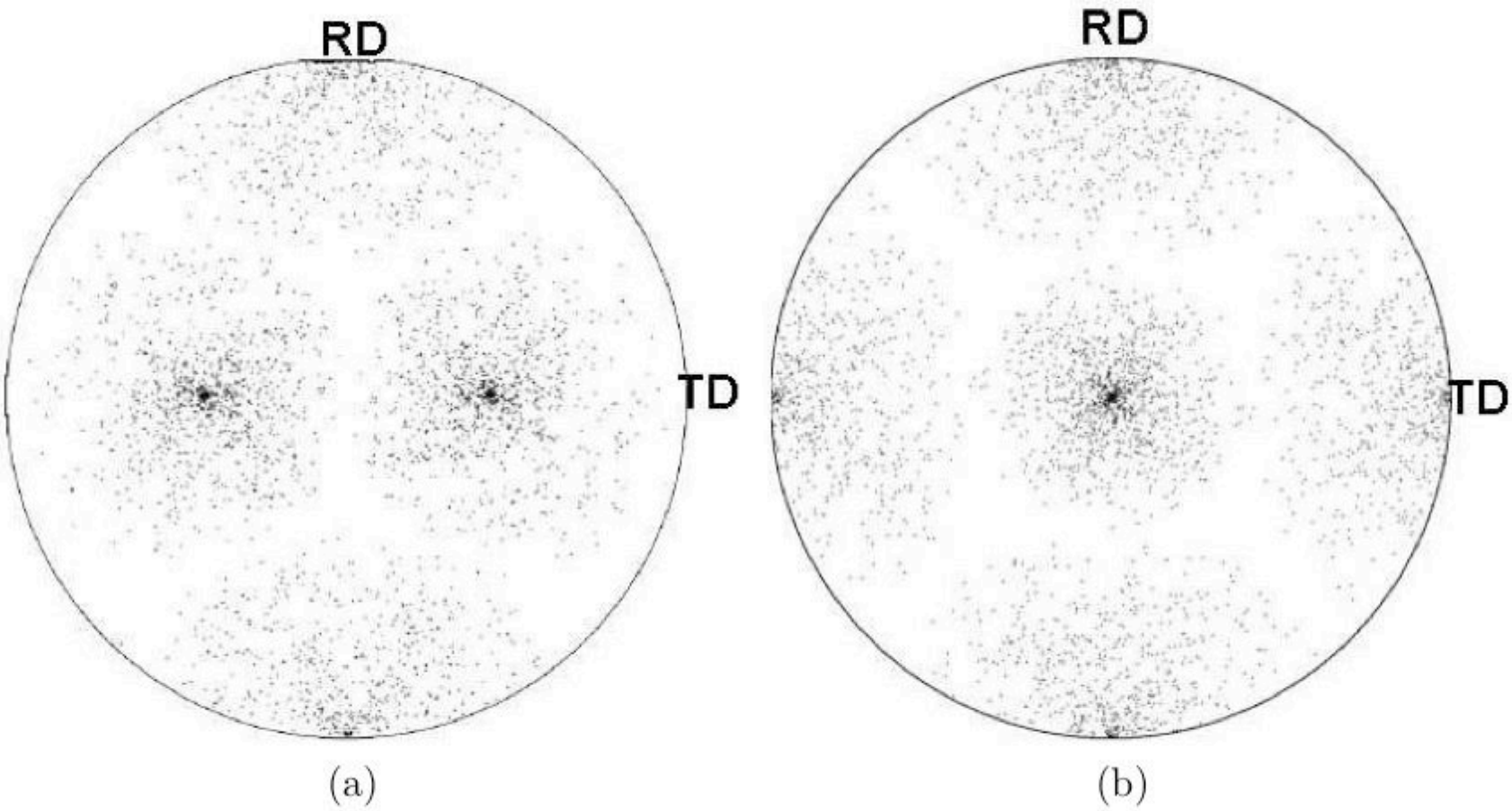
$$\mathbf{v} = \sum_{k=1}^{n}\sum_{j=1}^{24} \mathbf{P}_j^k \Delta\mathbf{u}_j^k + \left(\mathbf{u} - \sum_{k=1}^{n}\sum_{j=1}^{24} \Delta\mathbf{u}_j^k\right)$$


0.06
0.04
0.02
0
-0.02
-0.04
-0.06
True Strain
longitudinal
transverse
0
4
8
12
16
20
24
Active variants

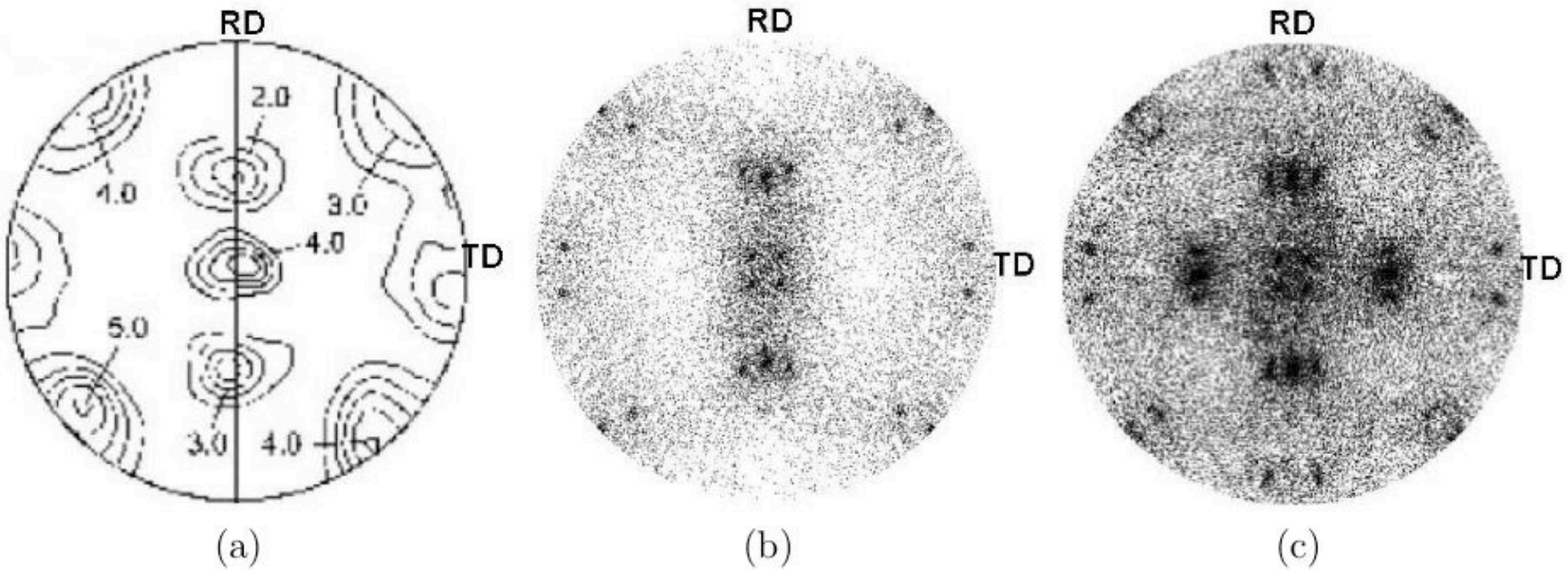

0.06
0.04
0.02
0
-0.02
-0.04
-0.06
True Strain
[100]s
[010]s
[001]s
0
4
8
12
16
20
24
Active variants

# Goss

# Cube

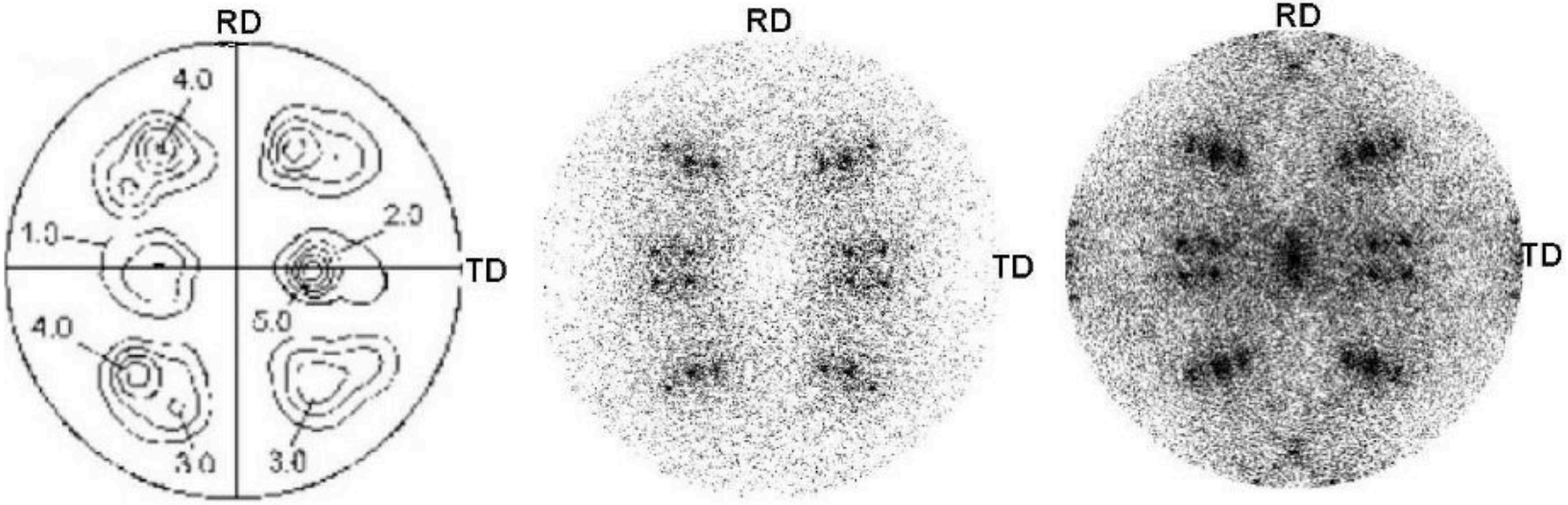


Experimental Calculated Calculated

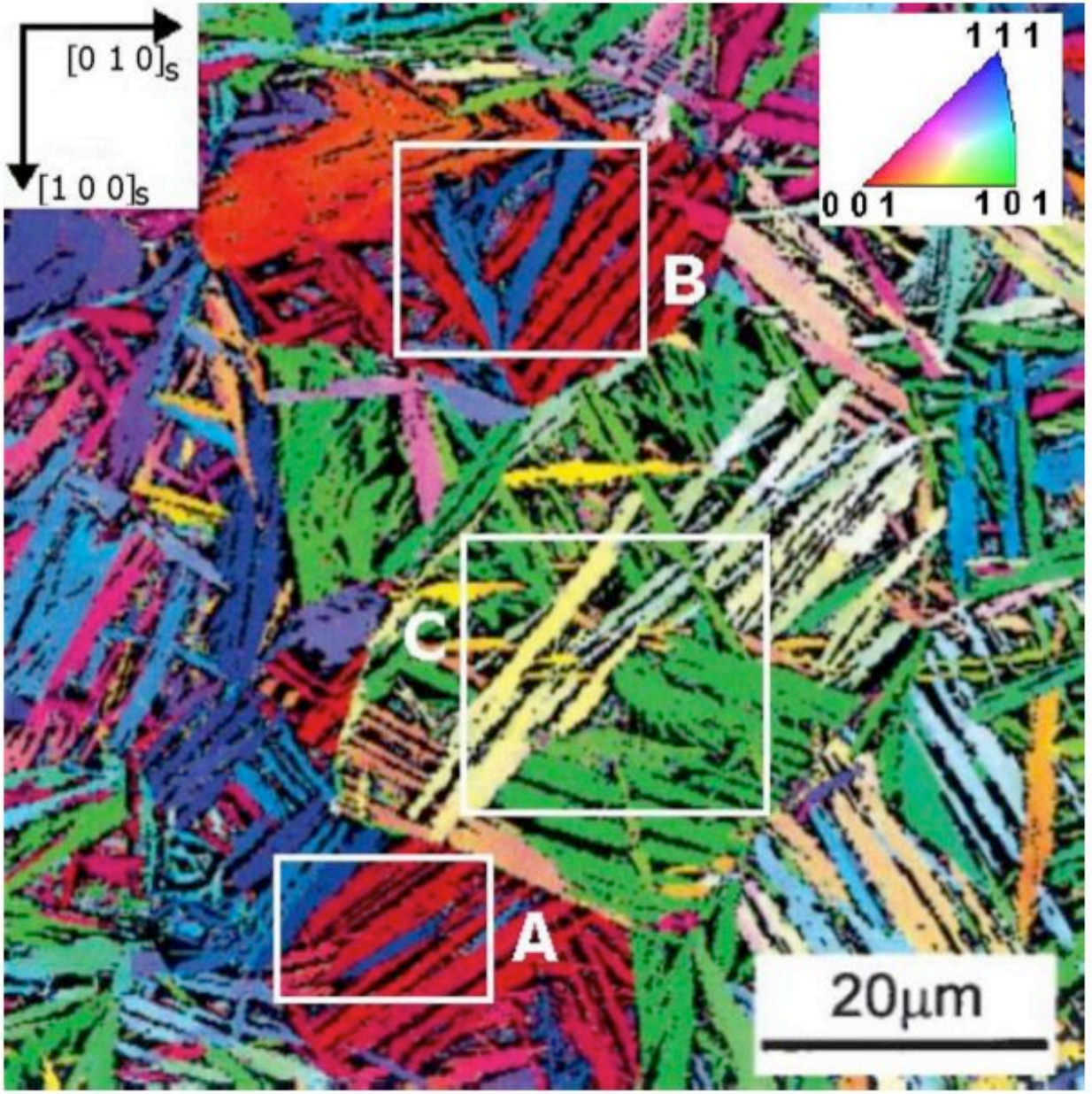



Kundu and Bhadeshia, Scripta Materialia 55 (2006) 779

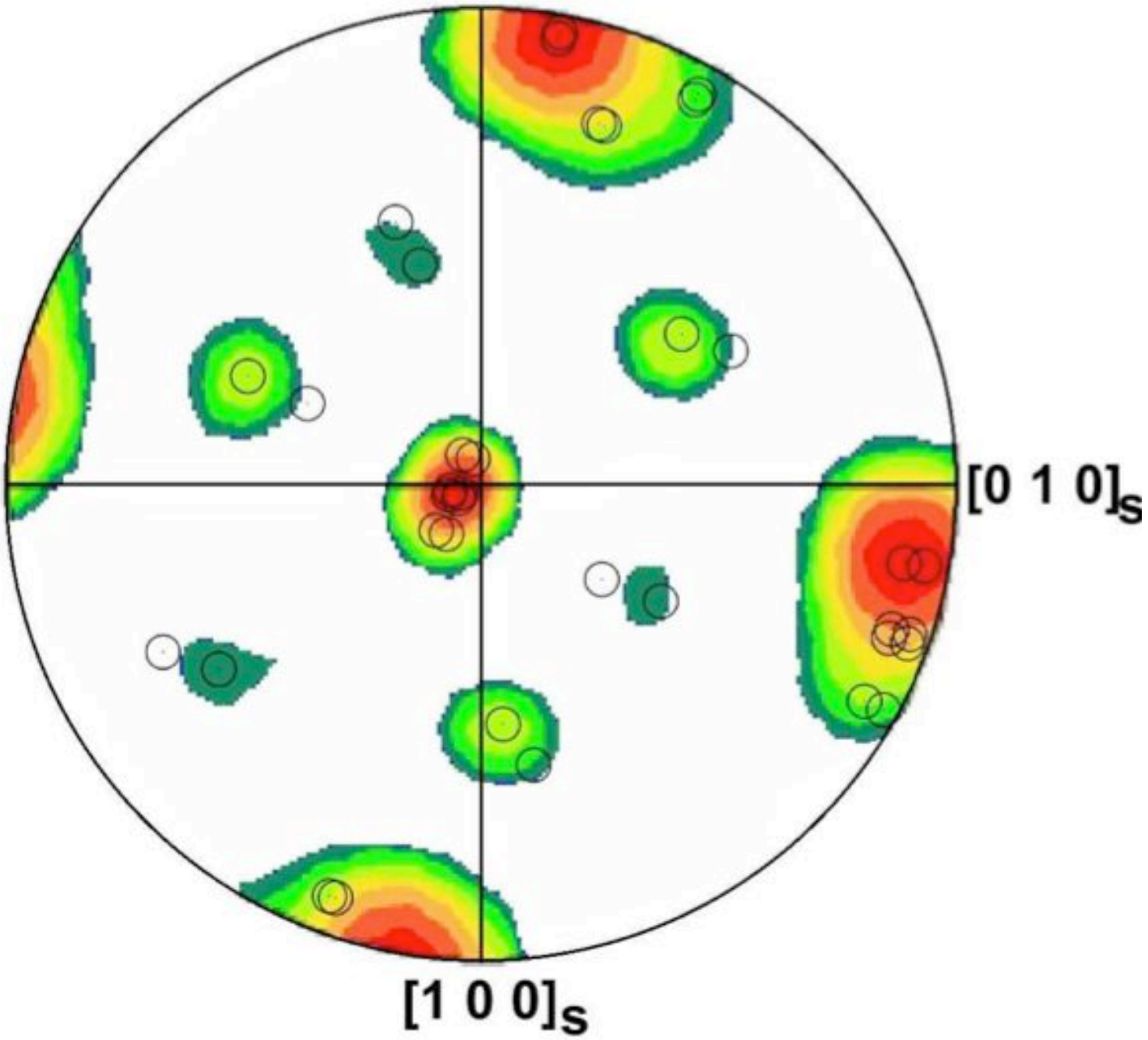
Experimental Calculated Calculated



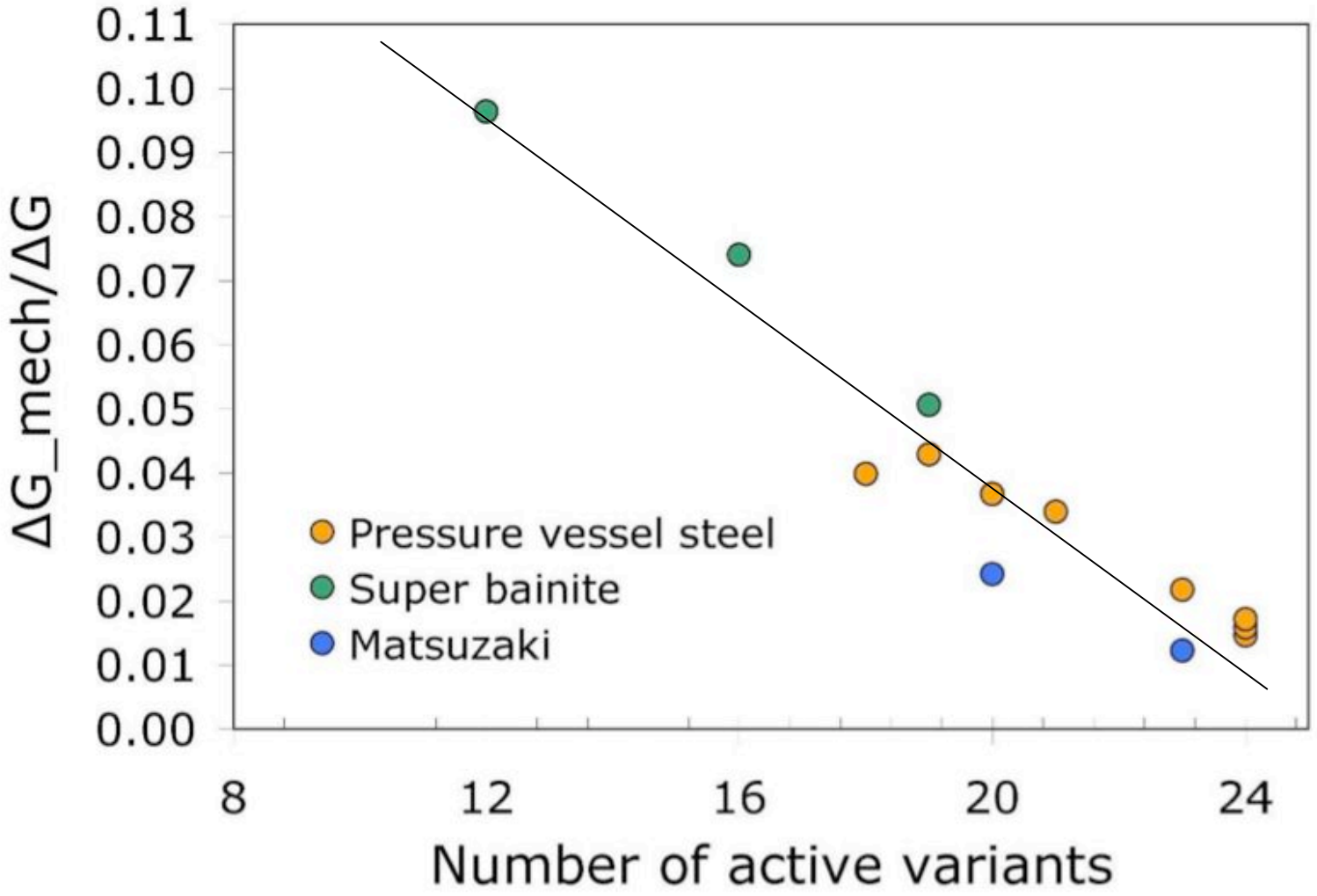

(a) (b) (c)

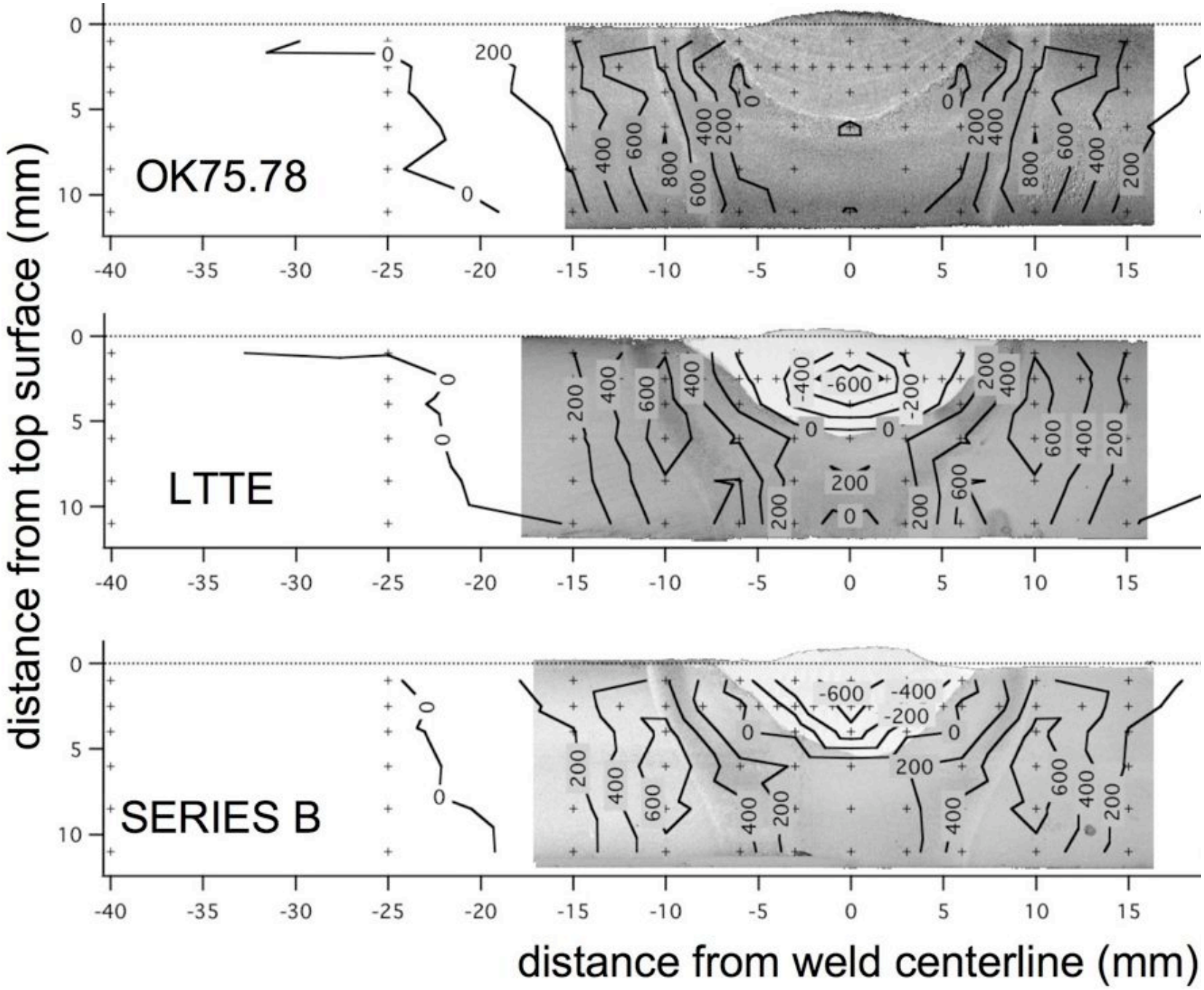



Kundu, Hase, Bhadeshia, Proc. Roy. Soc. 2007


[0 1 0]S
[1 0 0]S

$$\Delta G = \Delta G_{CHEM} + \Delta G_{MECH}$$




OK75.78
LTTE
SERIES B
distance from top surface (mm)
distance from weld centerline (mm)
0
5
10
-40
-35
-30
-25
-20
-15
-10
-5
0
5
10
15
200
400
600
800
-200
-400
-600