Low-temperature Bainite

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Motivation

Characterisation, tempering of novel bainitic microstructure

Atomic force microscopy of shape deformation

Mechanical property changes during tempering

Microstructural changes during tempering

Compositional changes during tempering

Theory (lattice parameters, hardness)

Techniques: X-ray, atom-probe, microscopy, mechanical properties, modelling theory

Intoduction

What is the novelty in the microstructure of so-called 'super-bainite'?

Forms at very low temperatures.

Tiny plates.

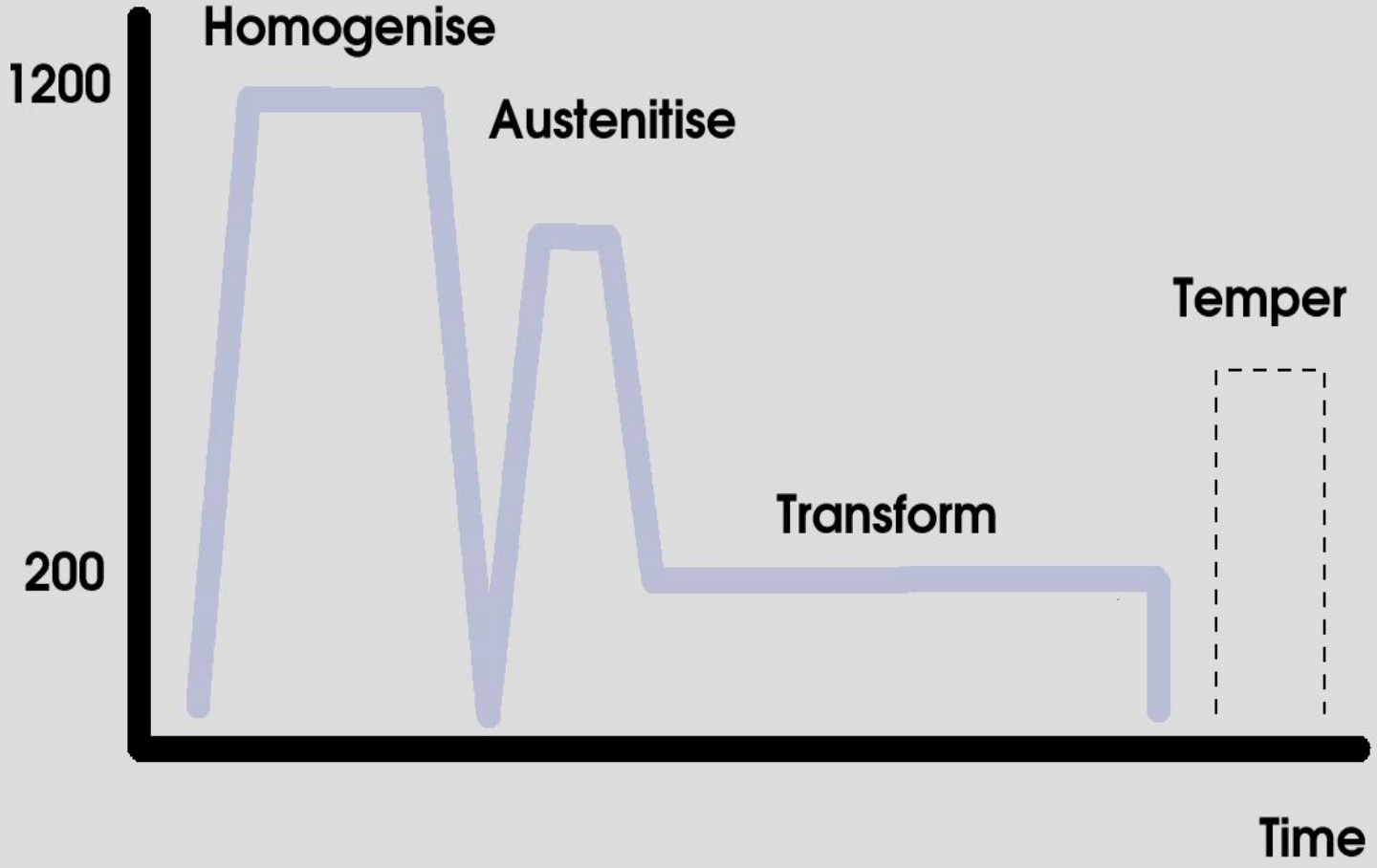
Very tempering resistant.

Wonderful mechanical properties in dirty state.

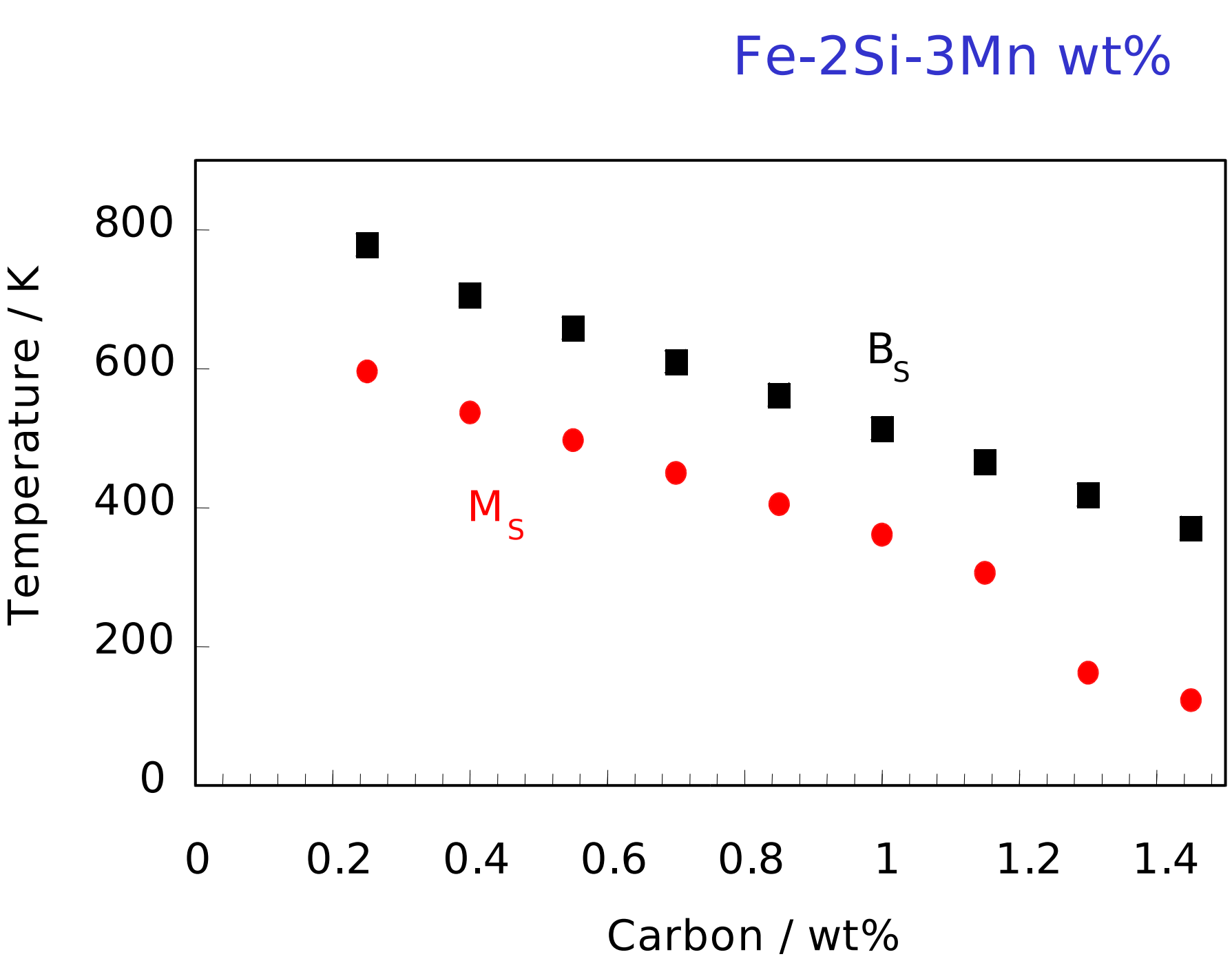
Composition

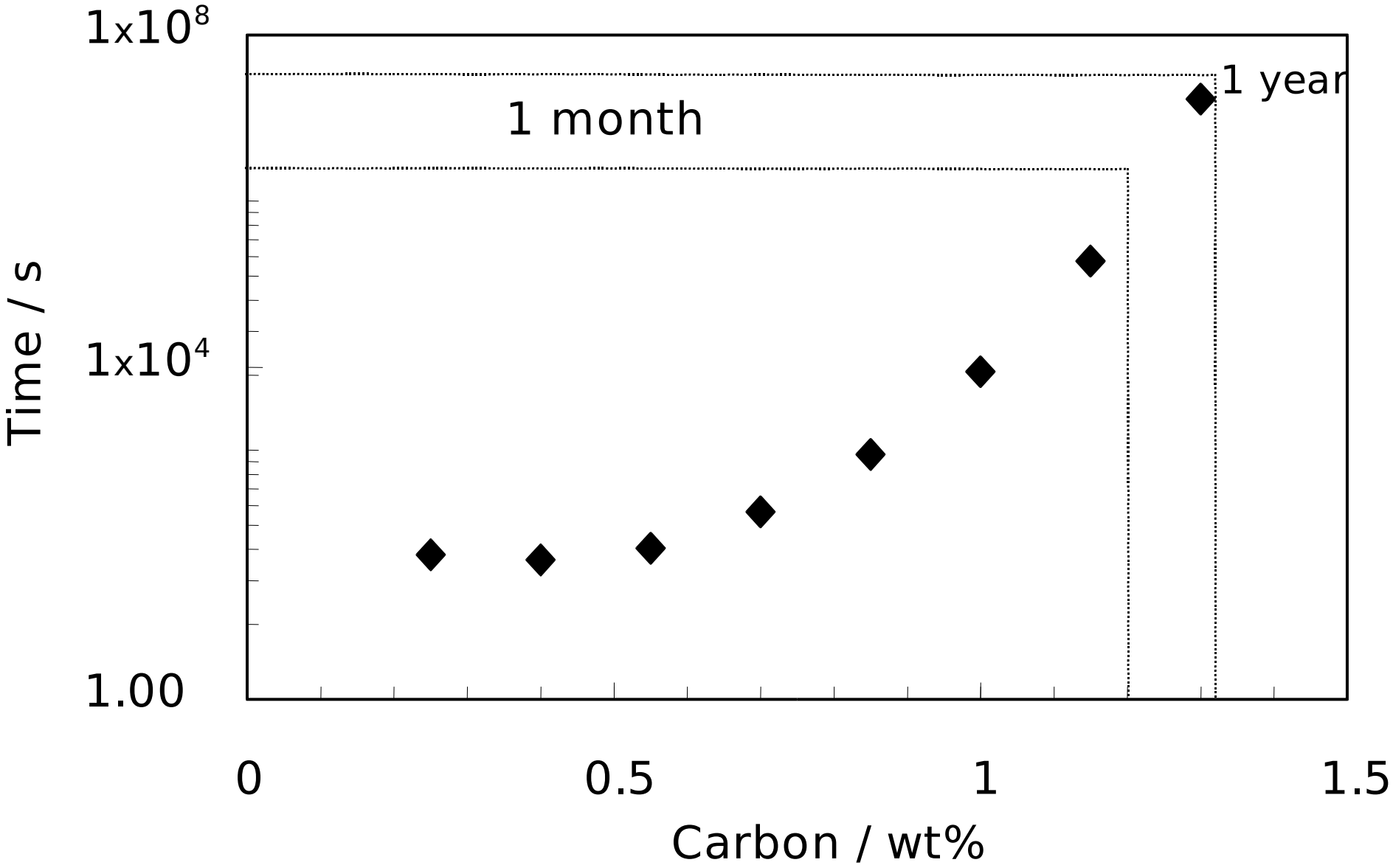
	C	Si	Mn	Mo	Cr	V
Wt %	0.75	1.63	1.95	0.28	1.48	0.1
At %	3.34	3.1	1.9	0.16	1.52	0.1

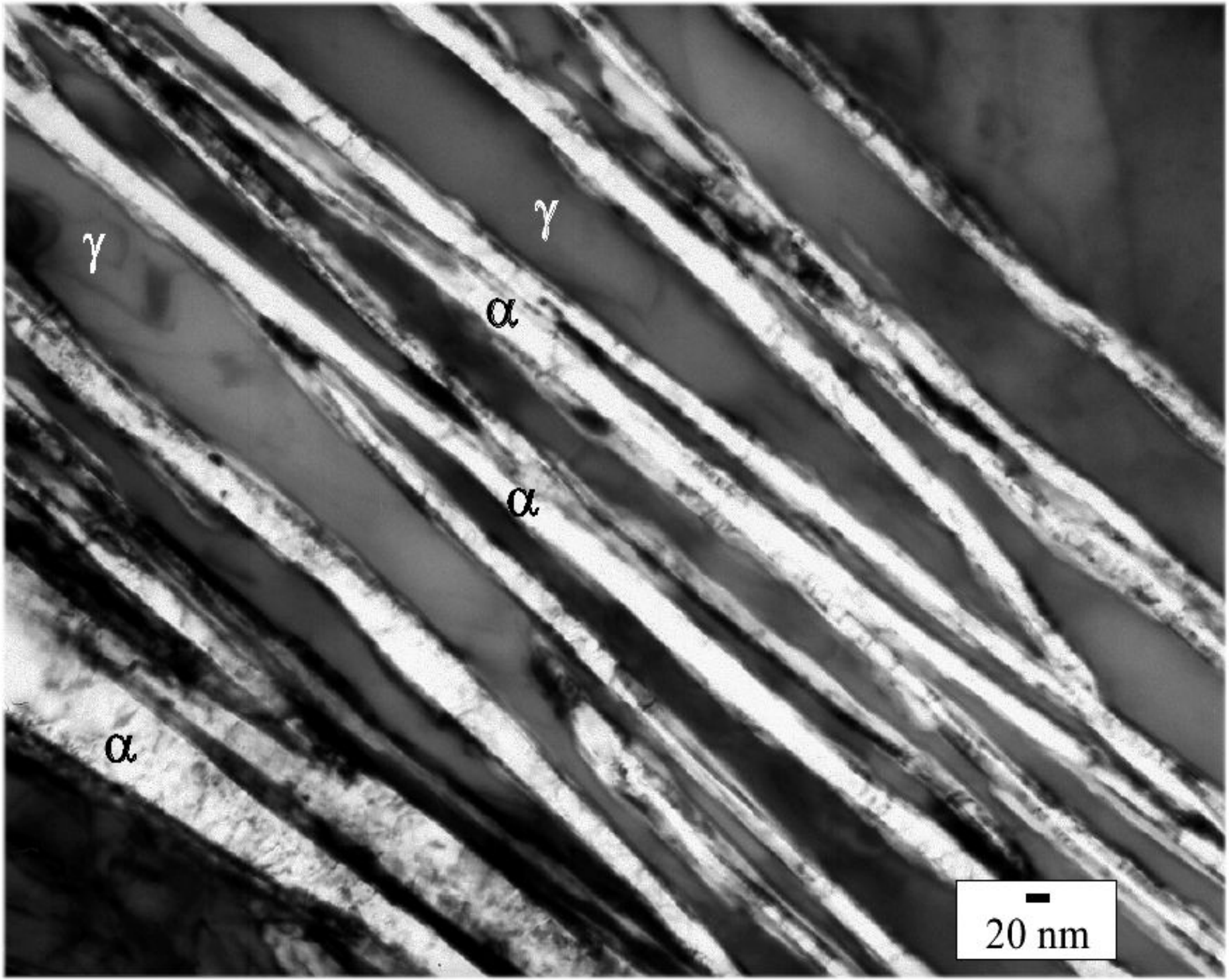
Low Temperature Bainite

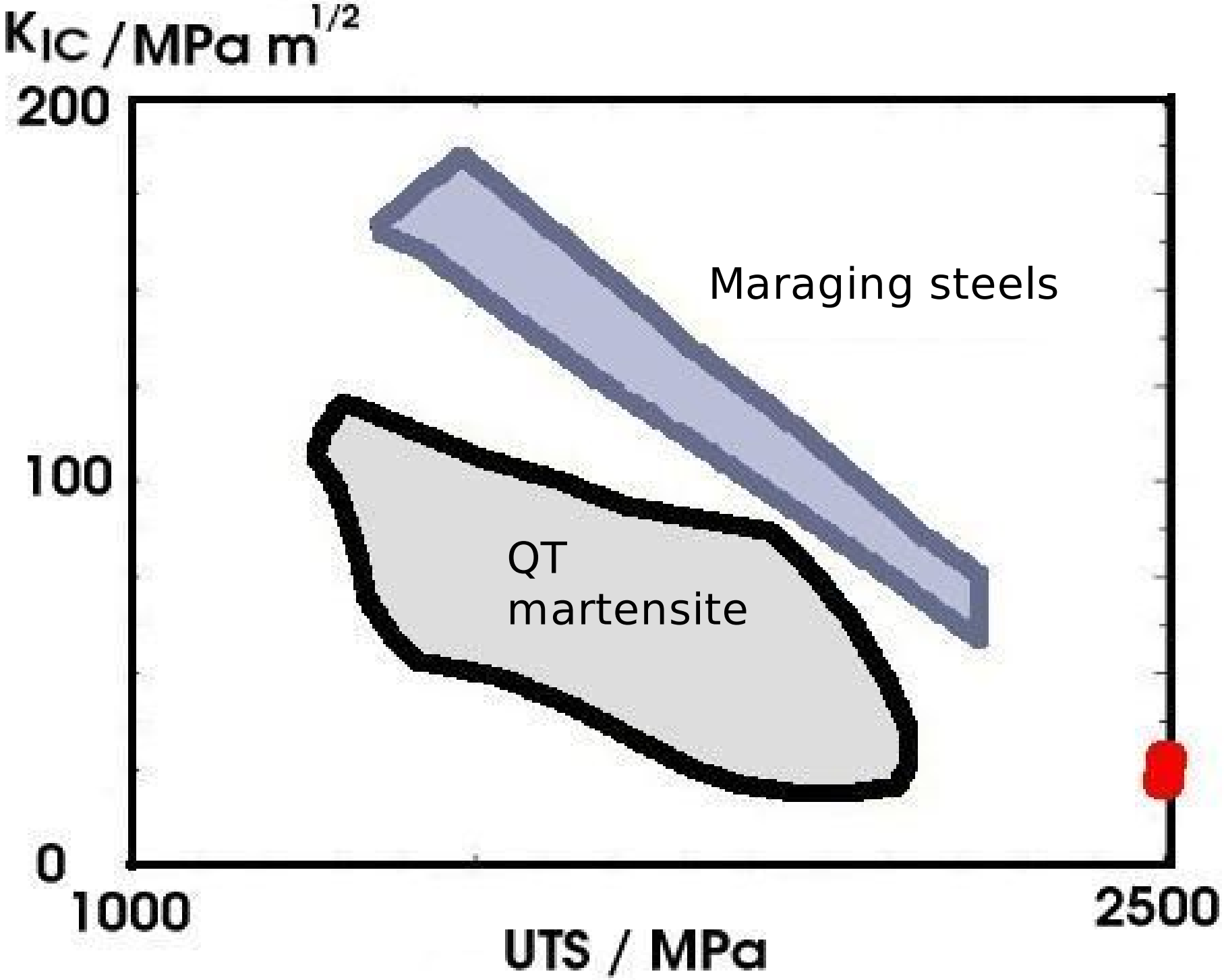


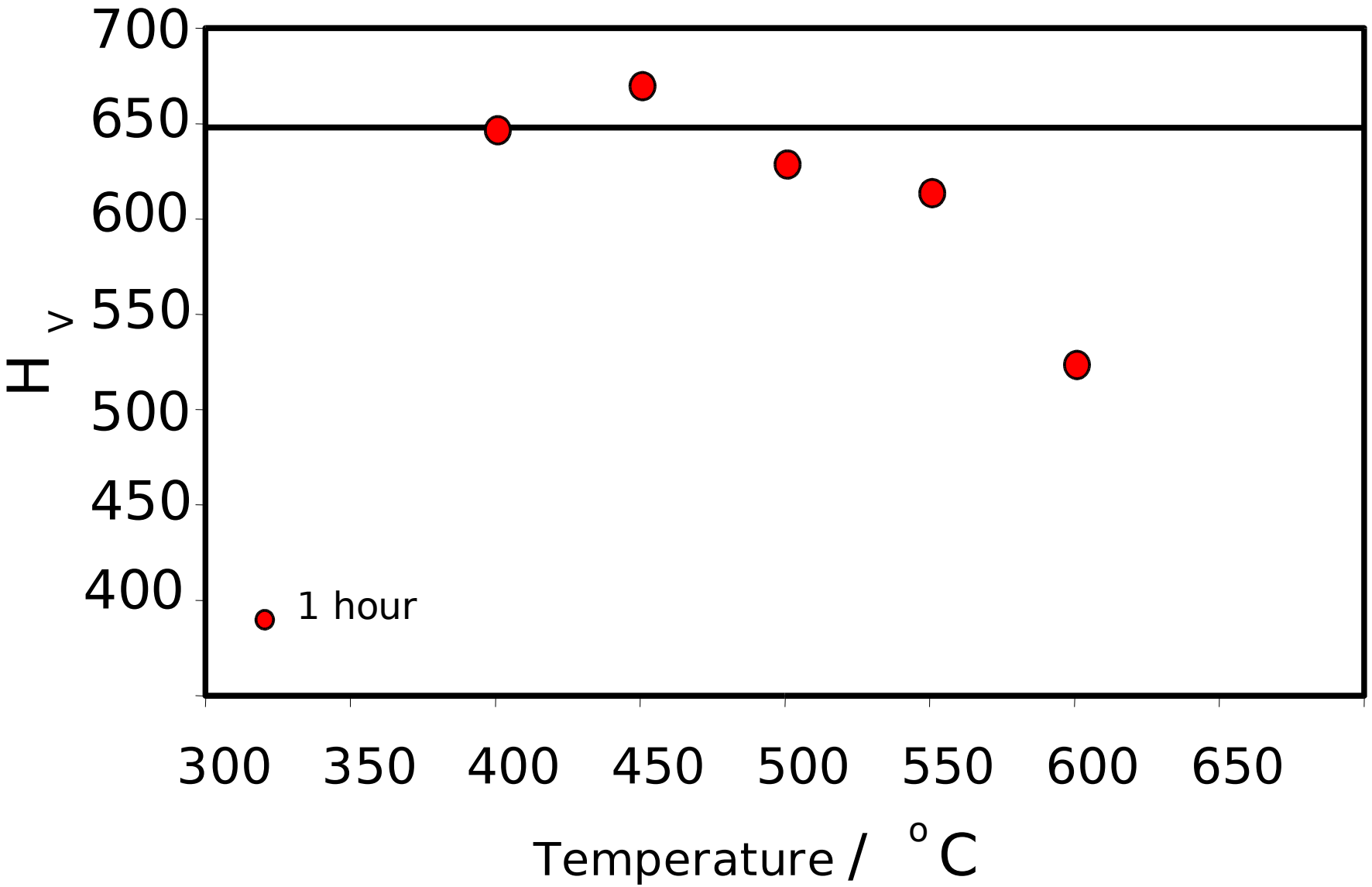
Isothermal transformation at 200°C for 10 days

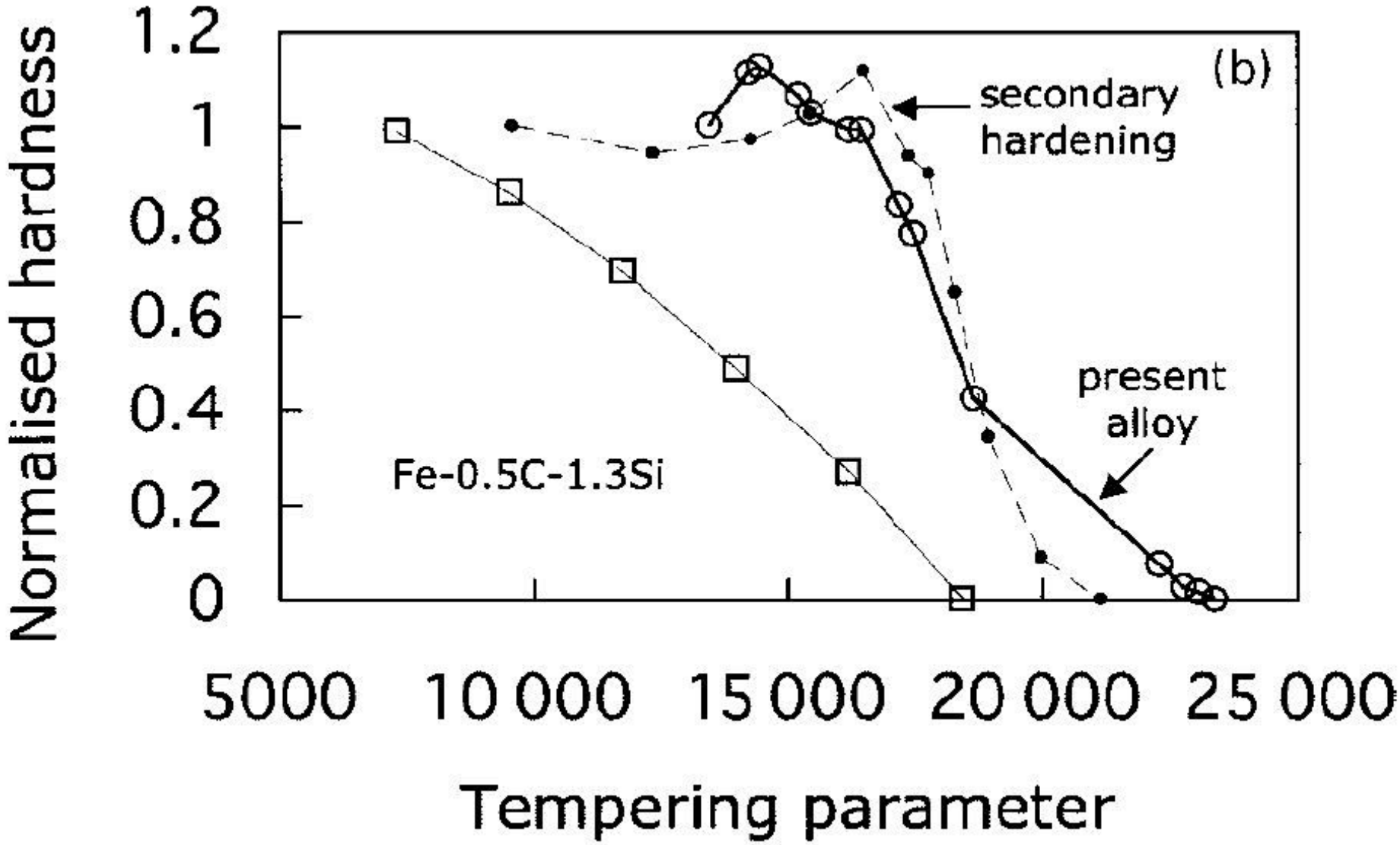

Fe-2Si-3Mn wt%
Temperature / K
800
600
400
200
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Carbon / wt%
B
S
M
S

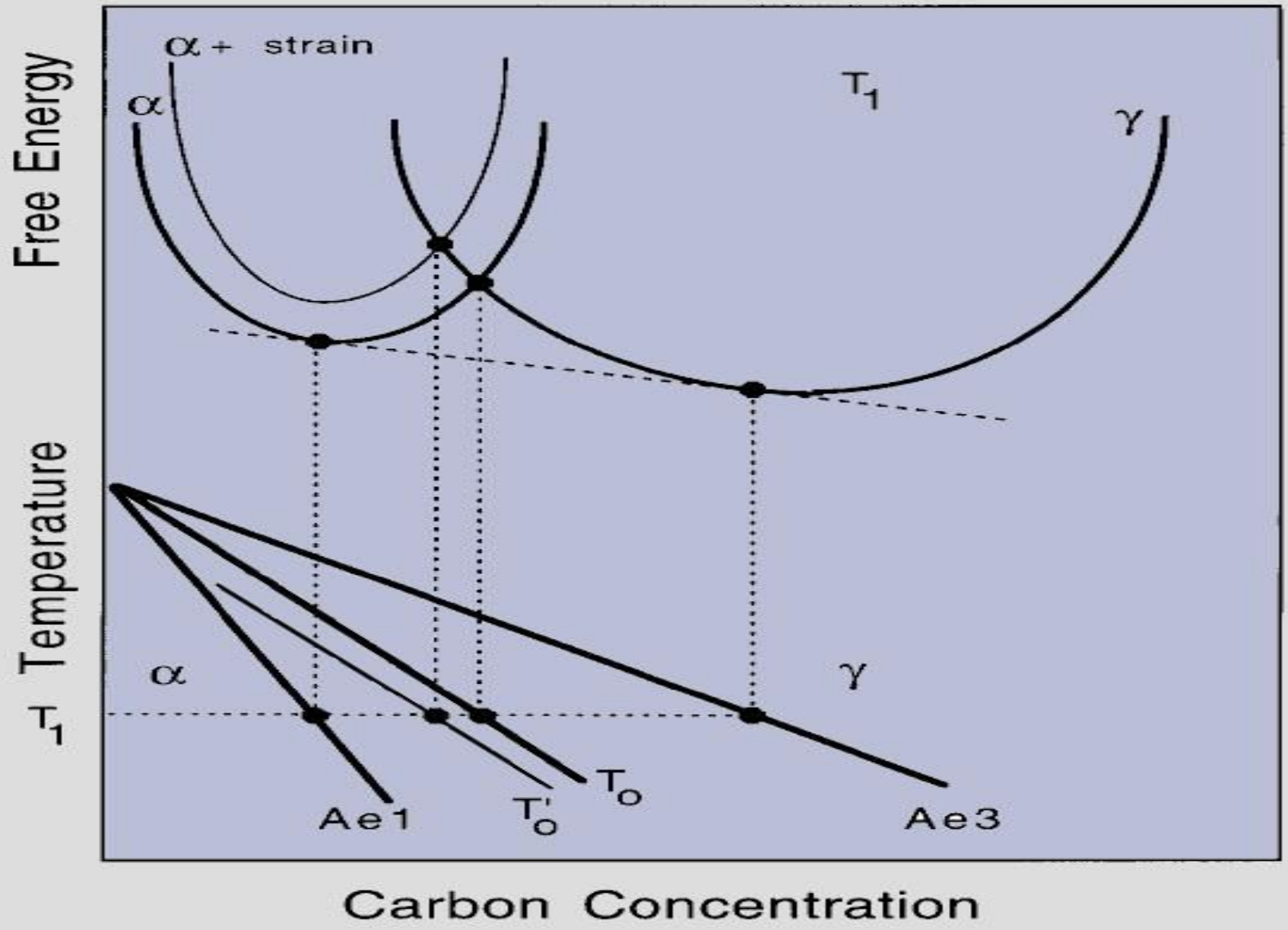

Fe-2Si-3Mn wt%
1x10^8
1x10^4
1.00
Time / s
1 month
1 year
0
0.5
1
1.5
Carbon / wt%


γ
γ
α
α
α
20 nm


K_{IC} / MPa $m^{1/2}$
200
100
0
1000
2500
UTS / MPa
Maraging steels
QT
martensite


700
650
600
550
500
450
400
H v
1 hour
300
350
400
450
500
550
600
650
Temperature / °C

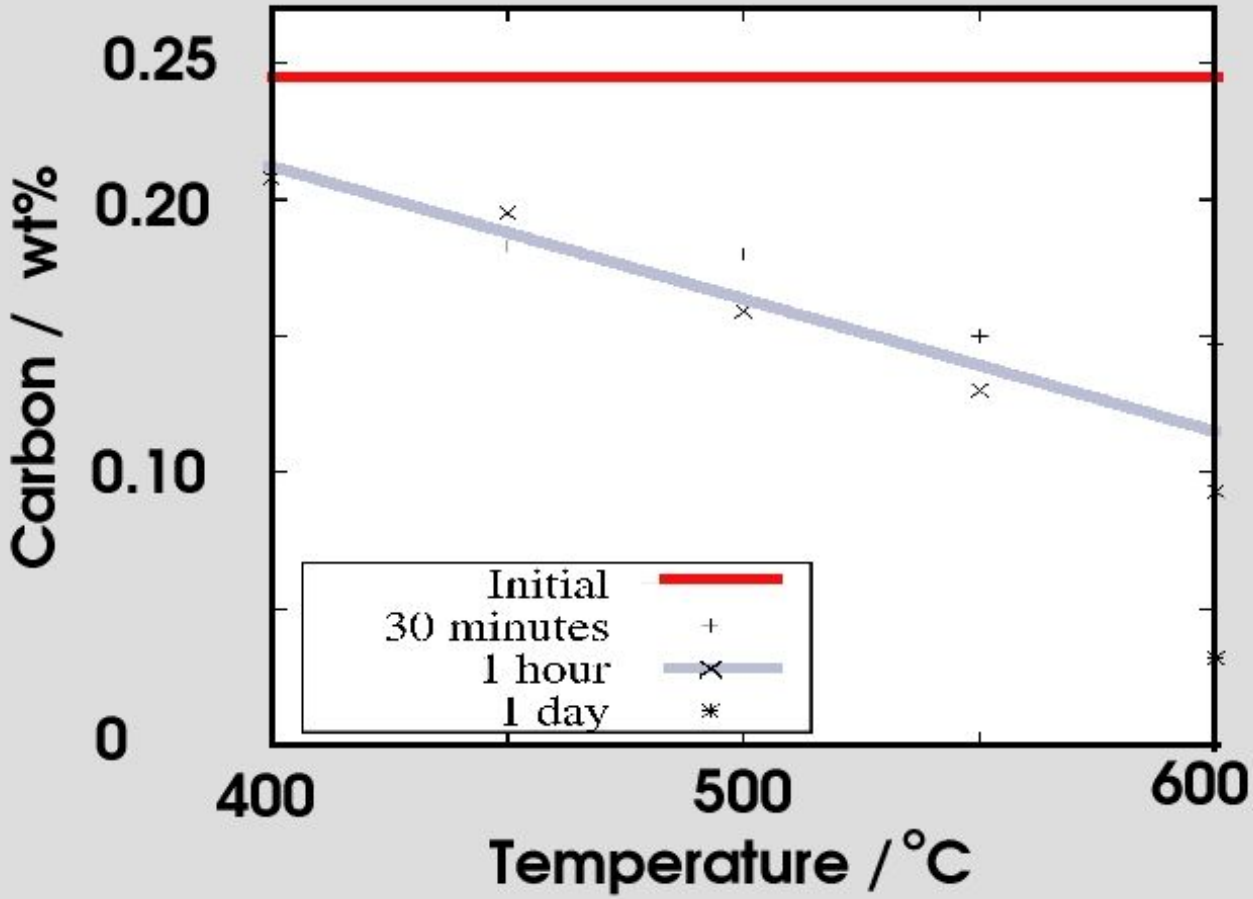

Normalised hardness
1.2
1
0.8
0.6
0.4
0.2
0
(b)
secondary
hardening
present
alloy
Fe-0.5C-1.3Si
5000
10 000
15 000
20 000
25 000
Tempering parameter



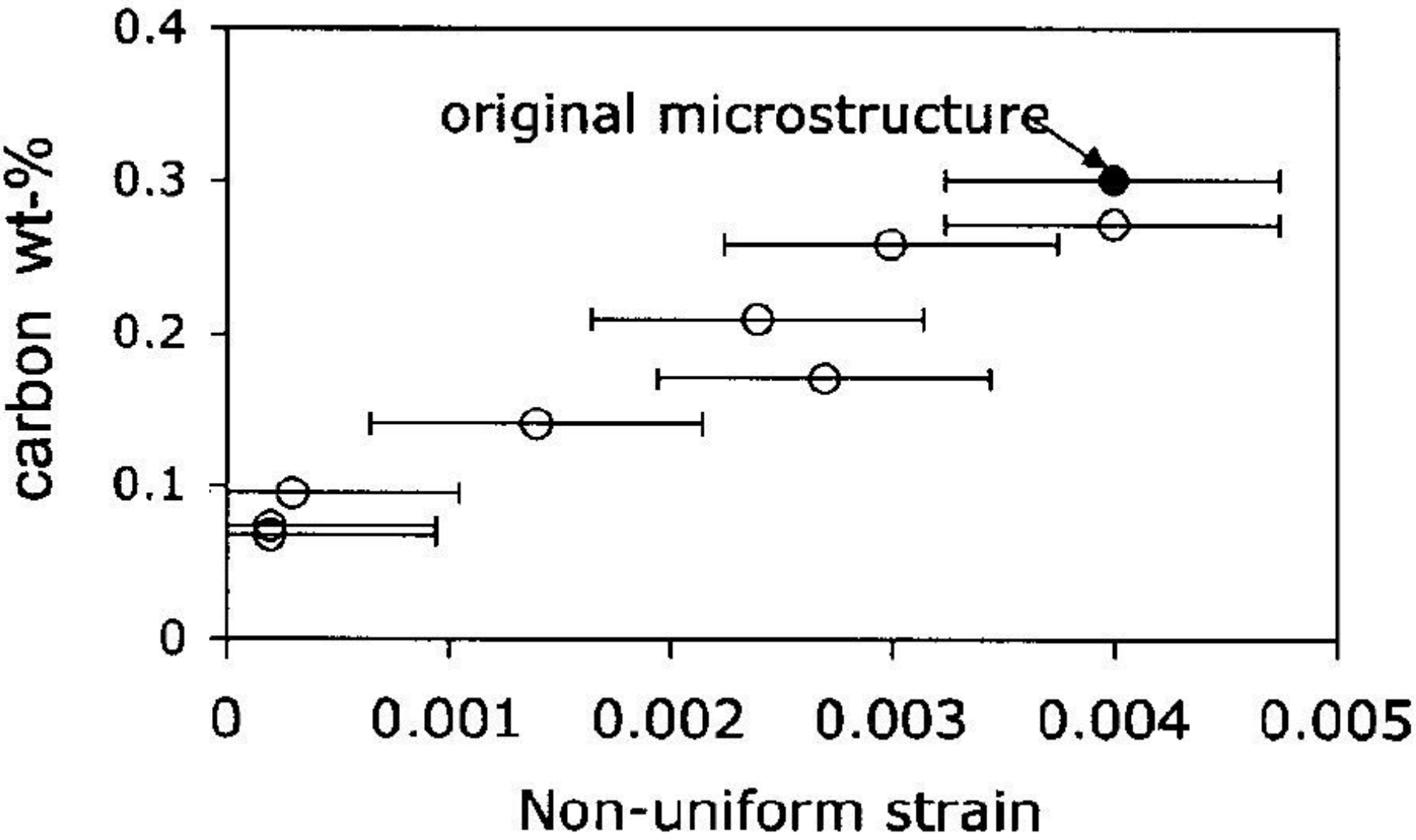
Bainite: diffusionless growth. Excess carbon subsequently partitioned into austenite.

Mystery of Carbon Content

Calculated from Lattice parameter of ferrite



Can we believe these results?

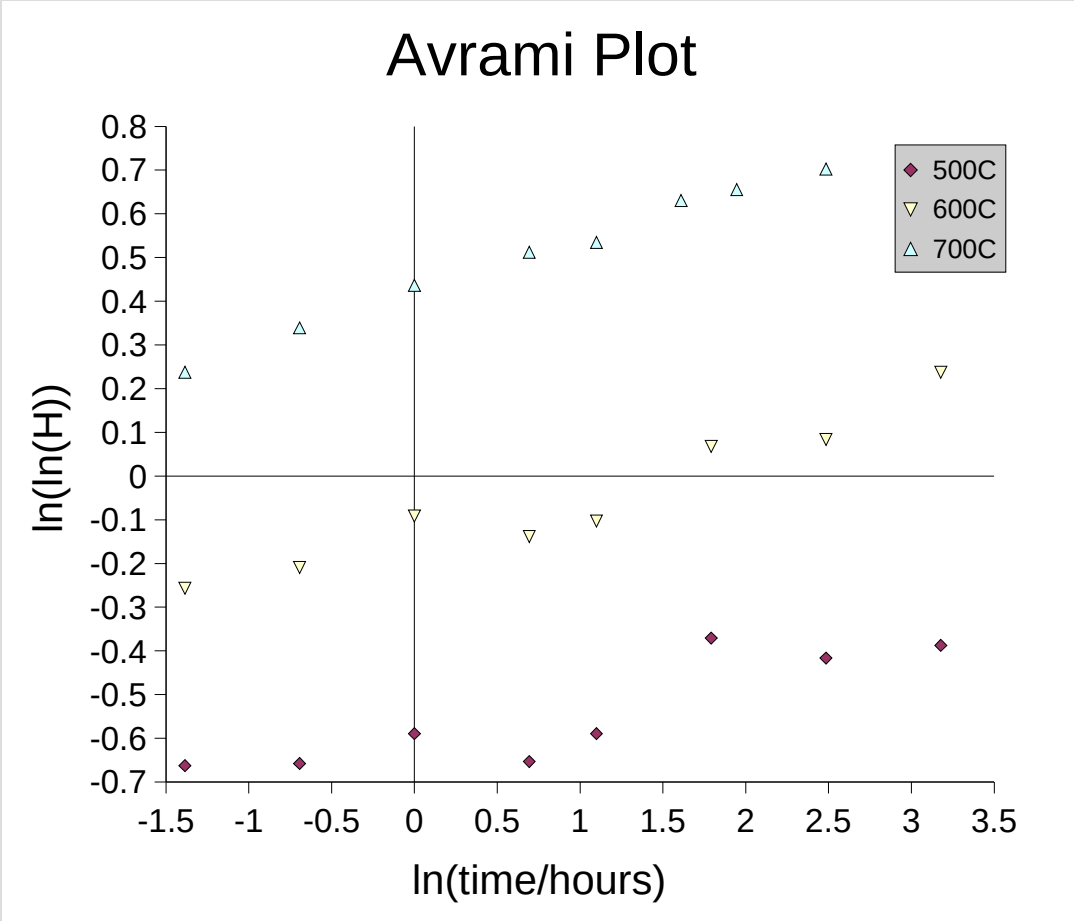

original microstructure
carbon wt-%
0.4
0.3
0.2
0.1
0
0
0.001
0.002
0.003
0.004
0.005
Non-uniform strain

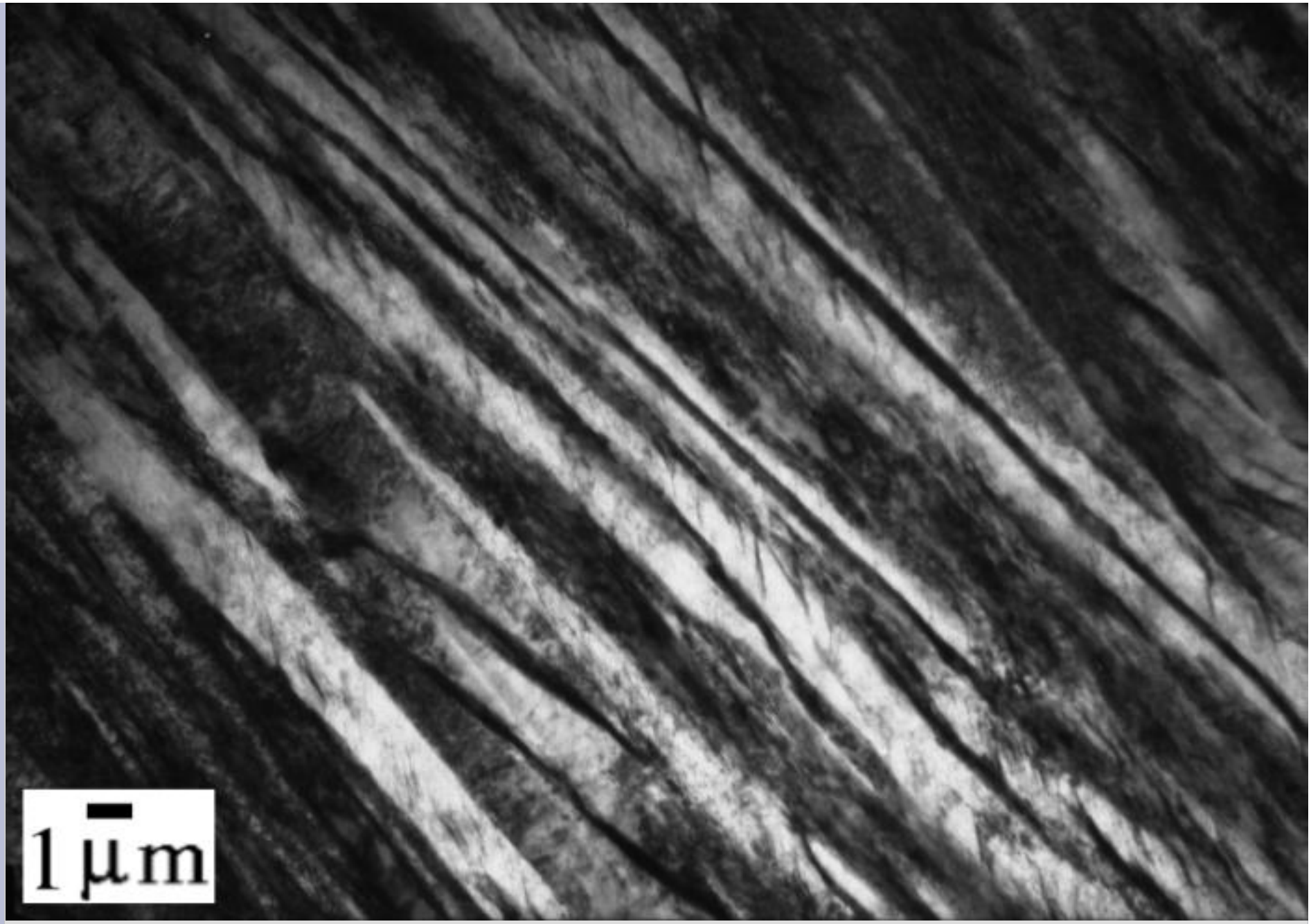
Tempering Resistance

$Q \sim 182\ kJ\ mol^{-1}$

Activation energy for carbon diffusion is 50 $kJmol^{-1}$

$\sim 200\ kJmol^{-1}$ for bulk diffusion of substitutional elements.





Aus1 fully transformed after 200°C for 10 days

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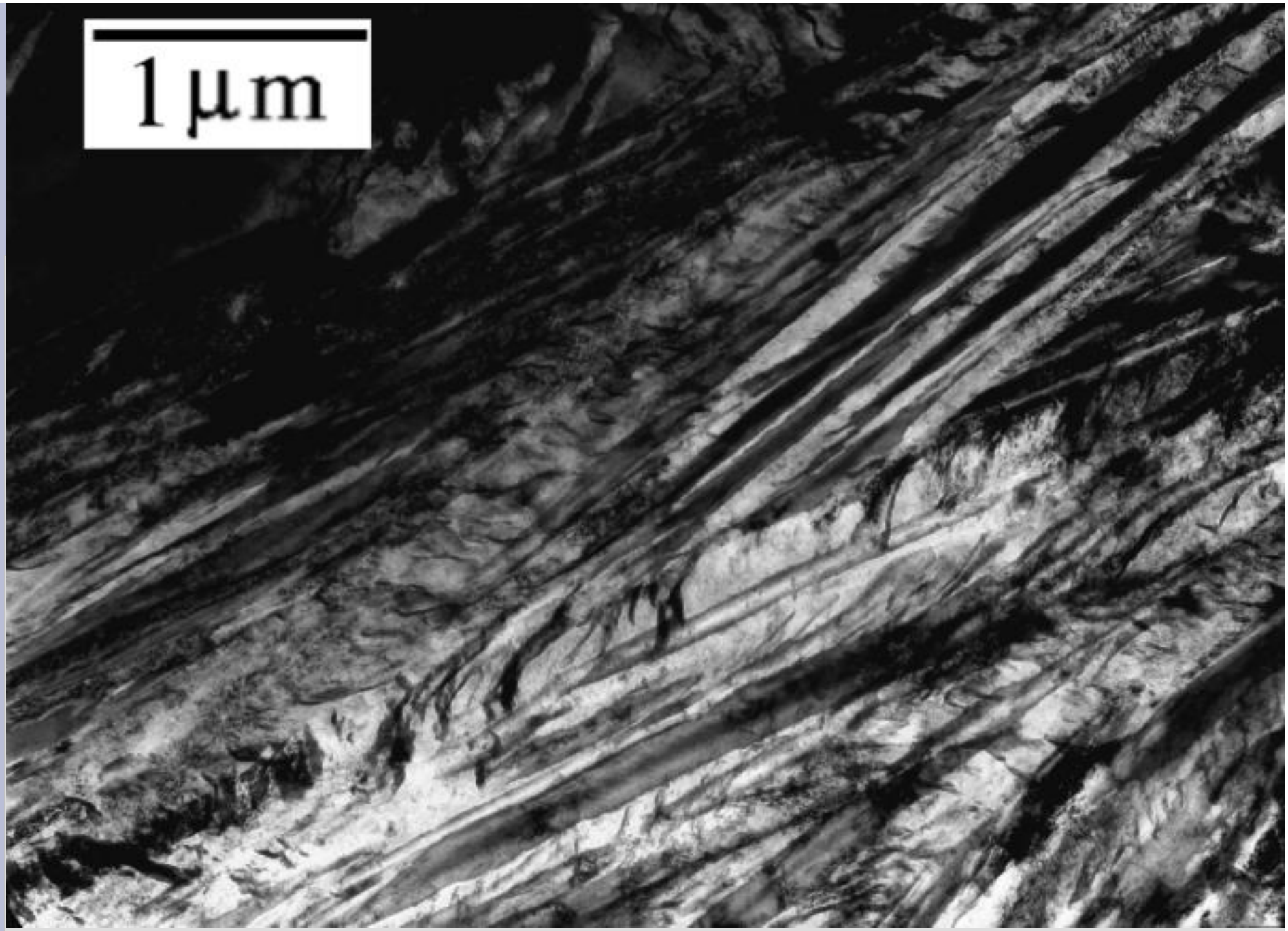
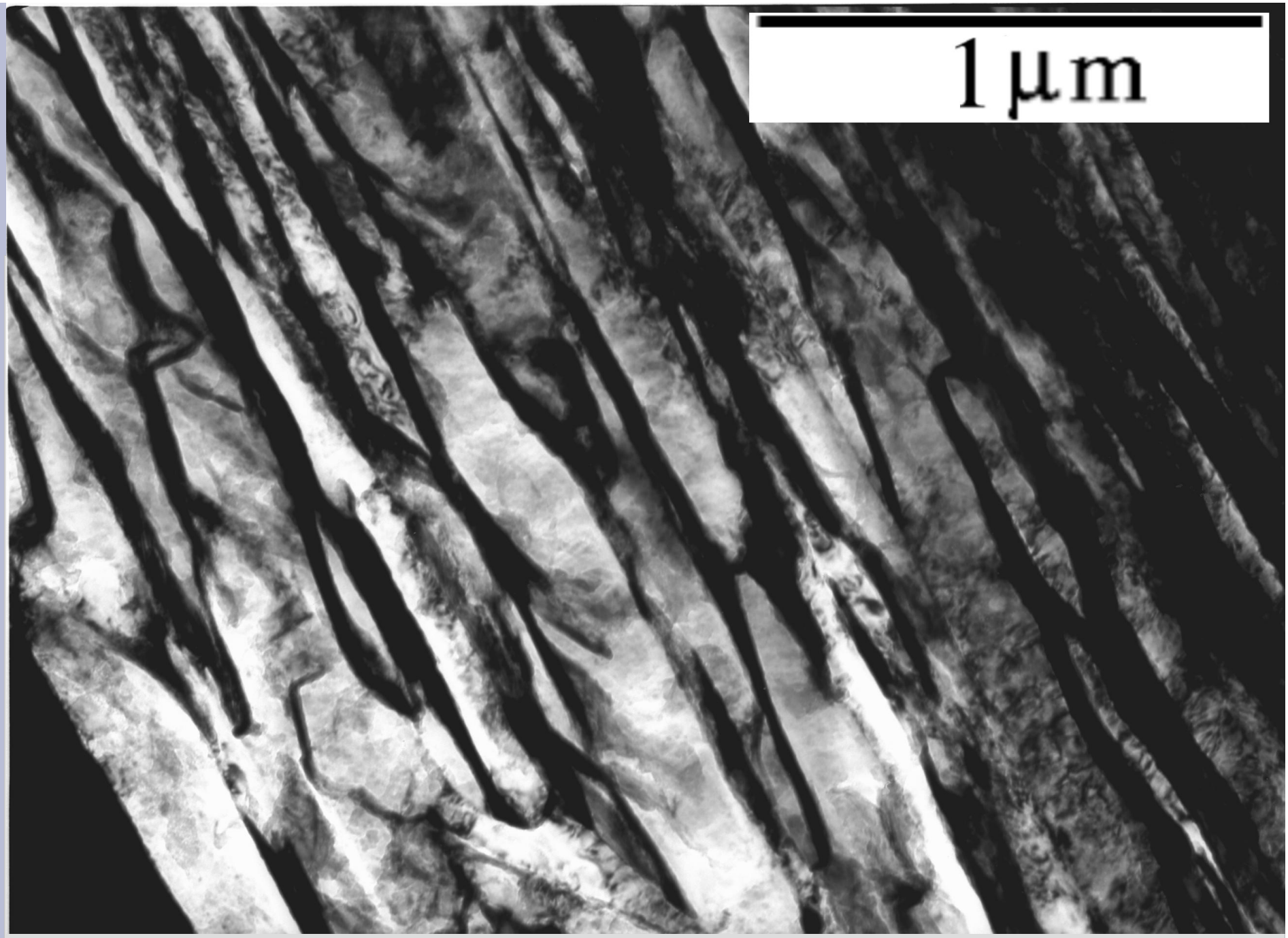
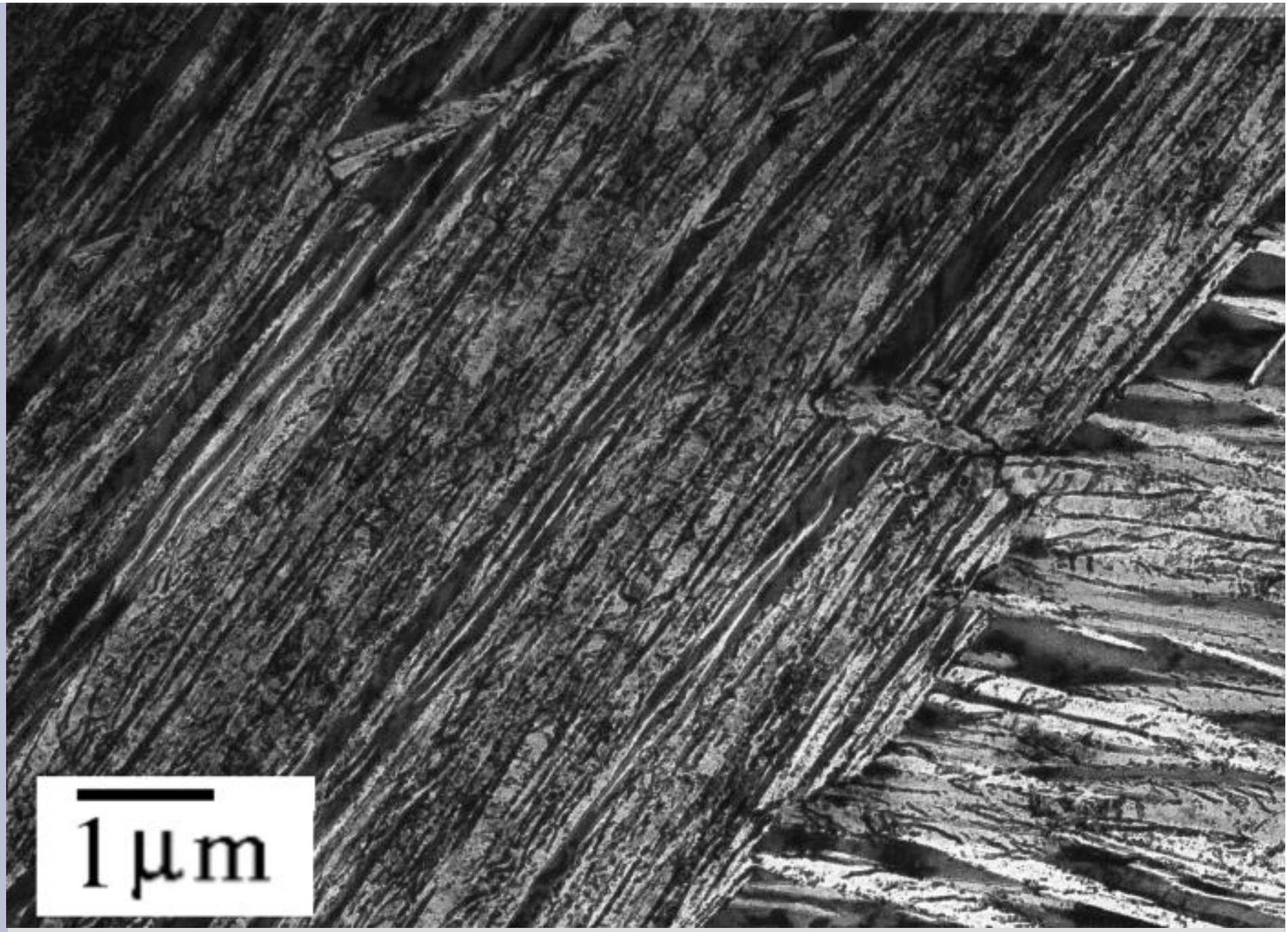


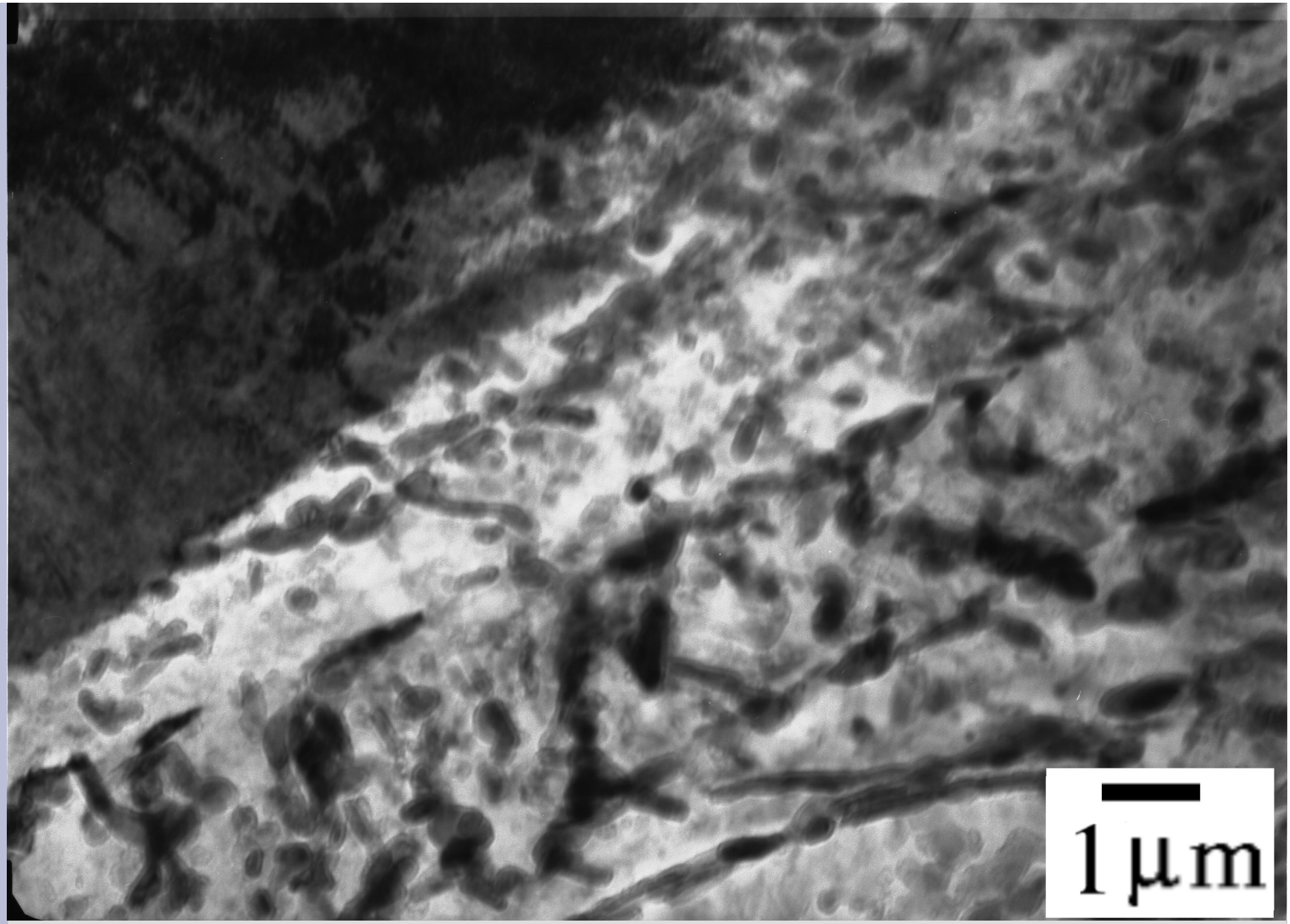
+ 30 min at 400°C



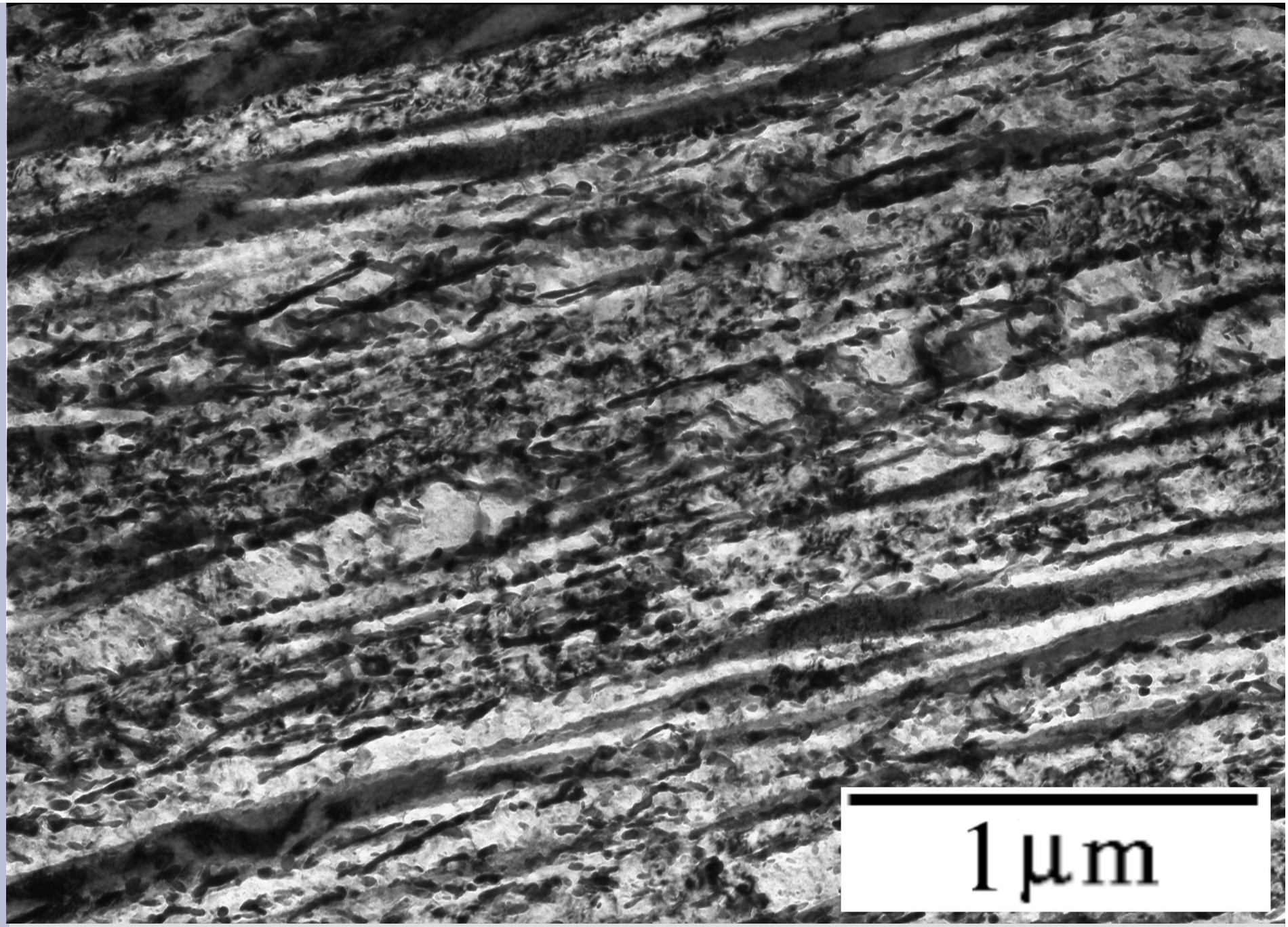
+ 1 h at 400ºC



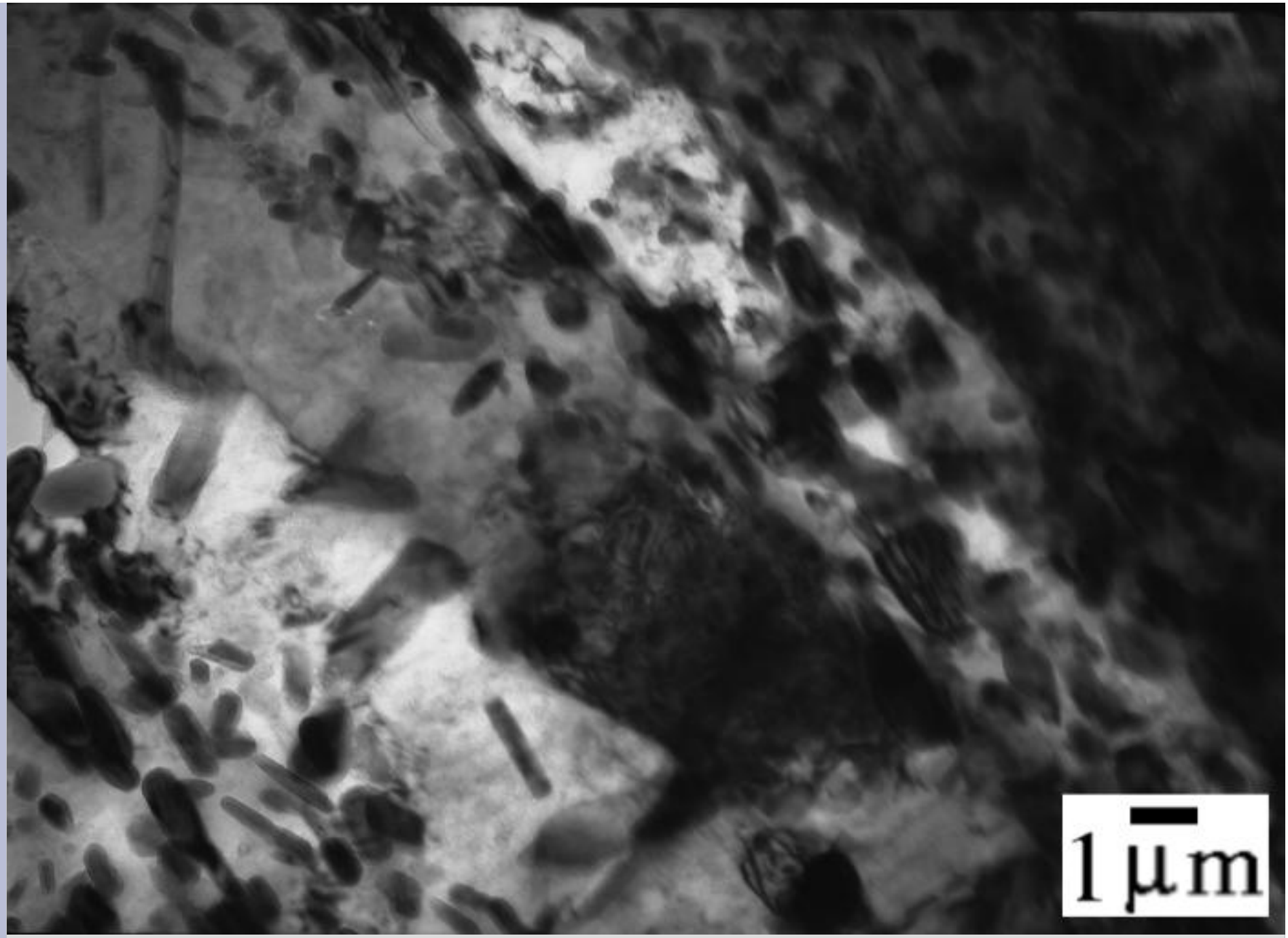
+ 1 h at 450°C



+ 1 h at 550°C



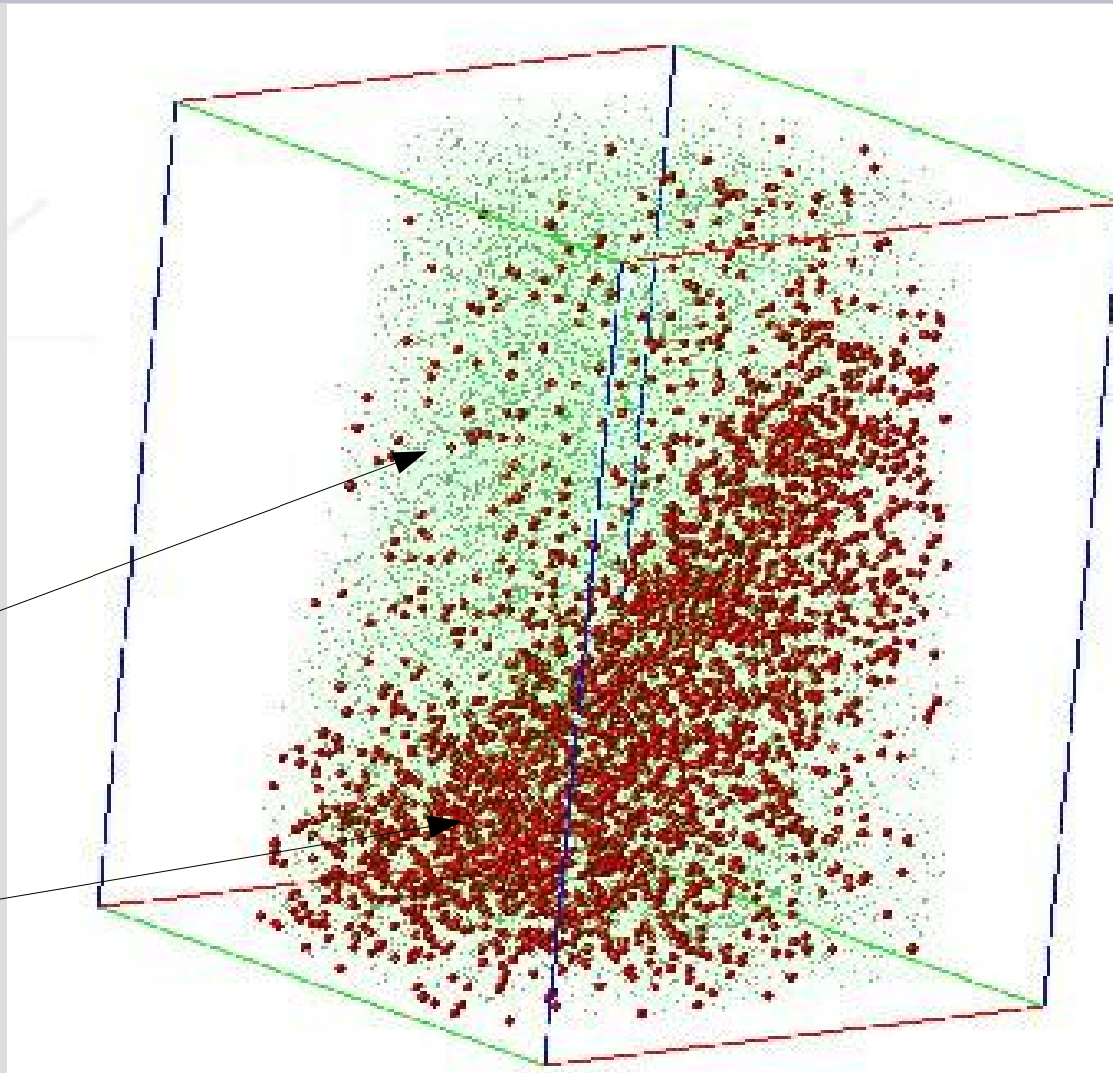
+ 1 h at 450°C

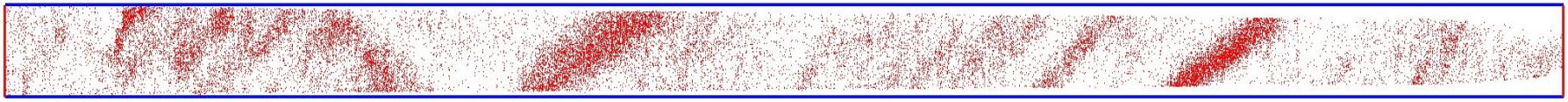


+ 24 h at 600°C

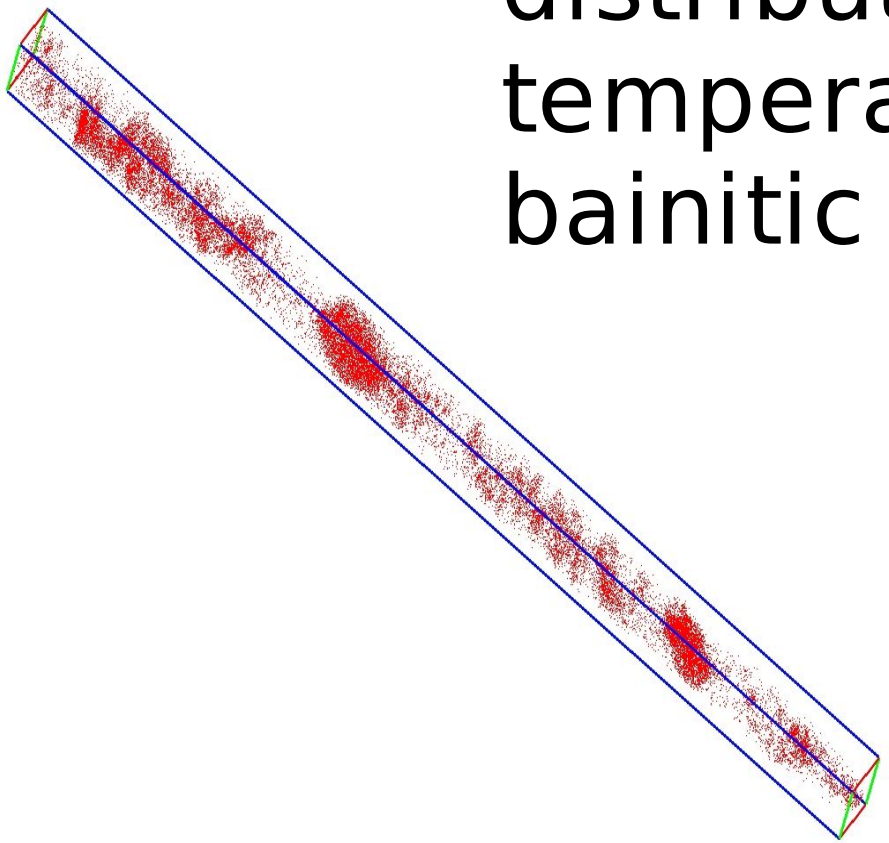
Atom Probe

Each dot is an atom, its position and composition known

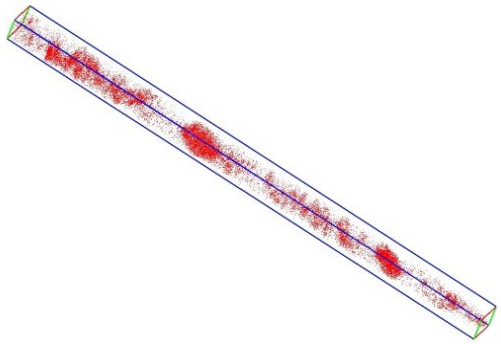


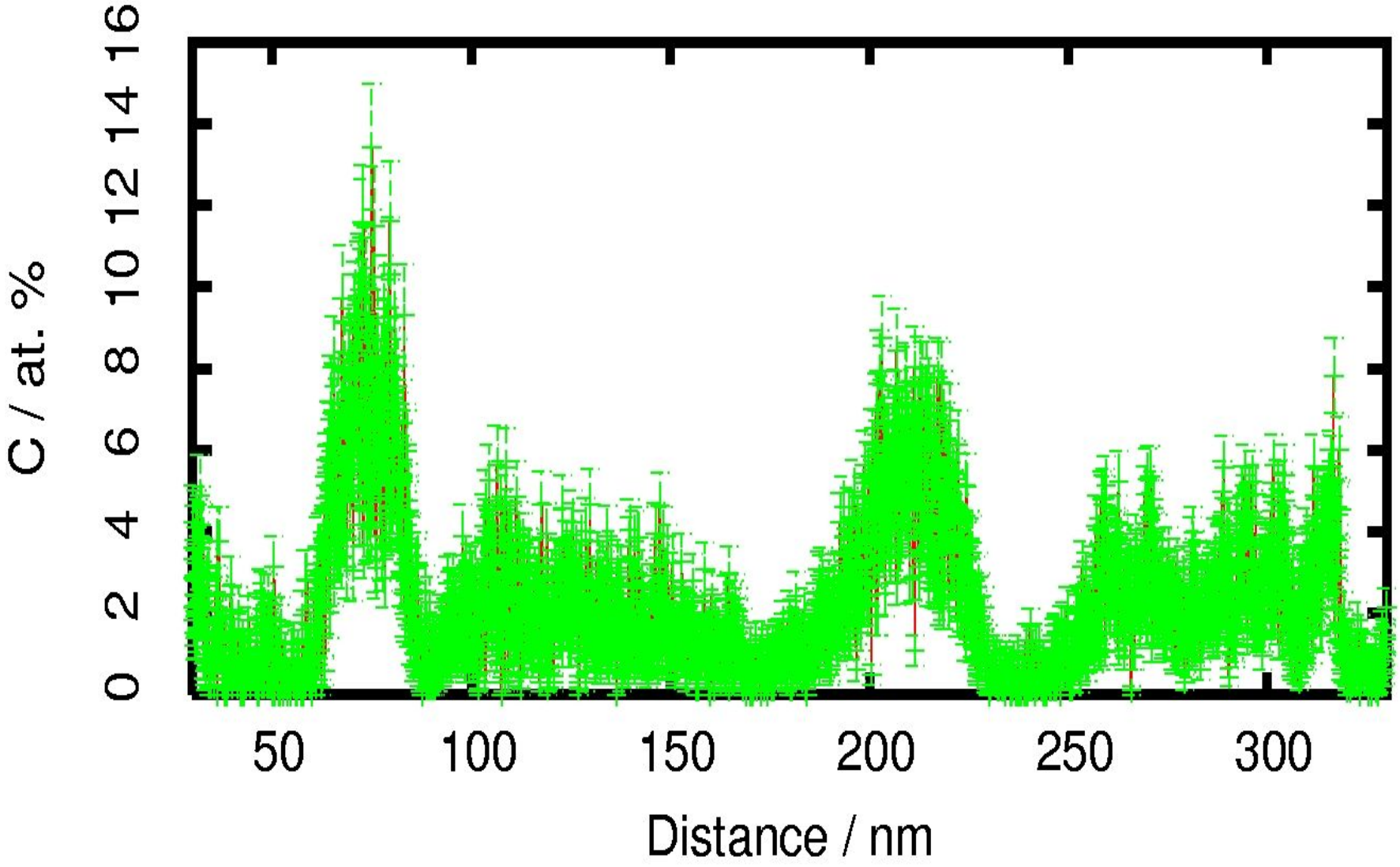


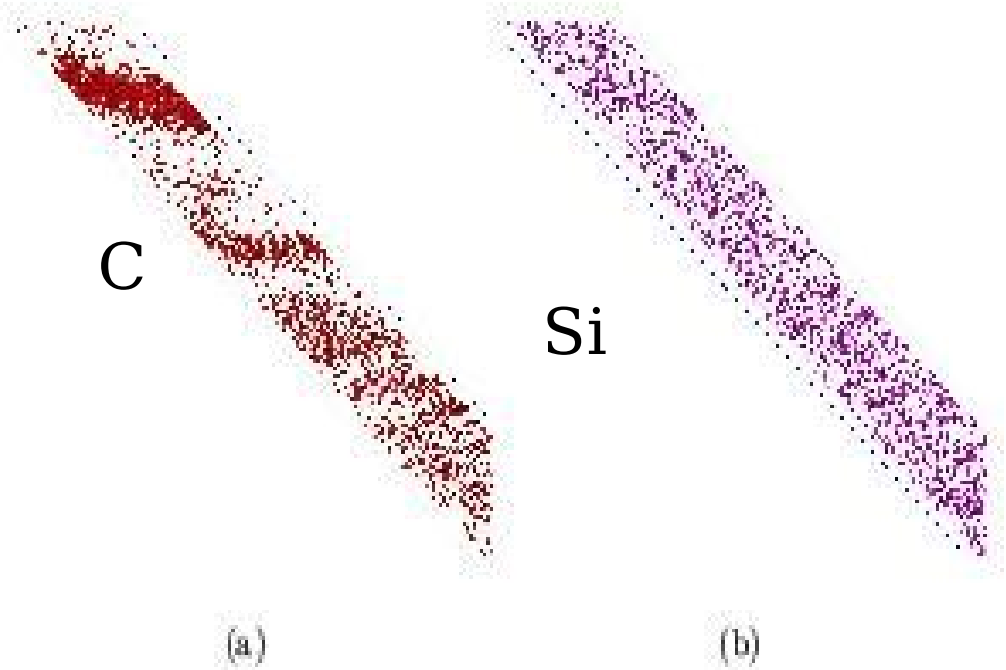
Carbon distribution in low temperature bainitic steel

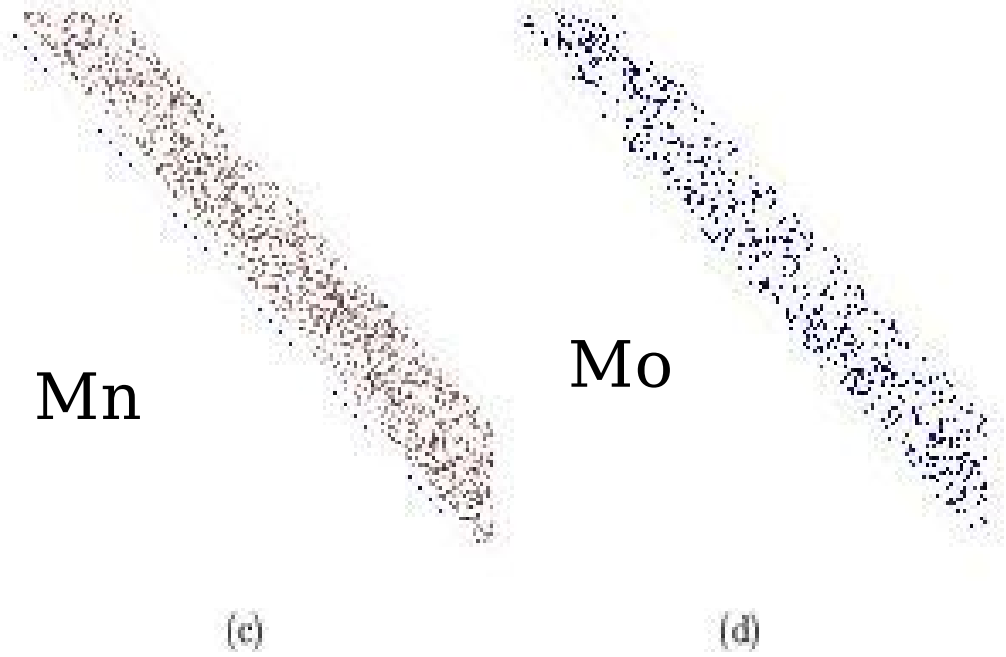


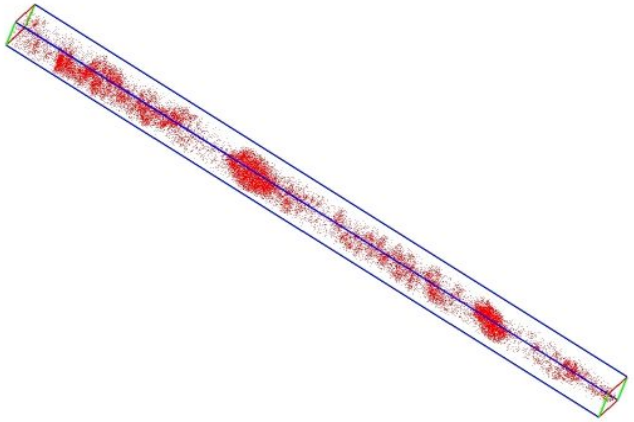
Collosal (12 at%) in austenite
Impressive (1.8 at%) in ferrite



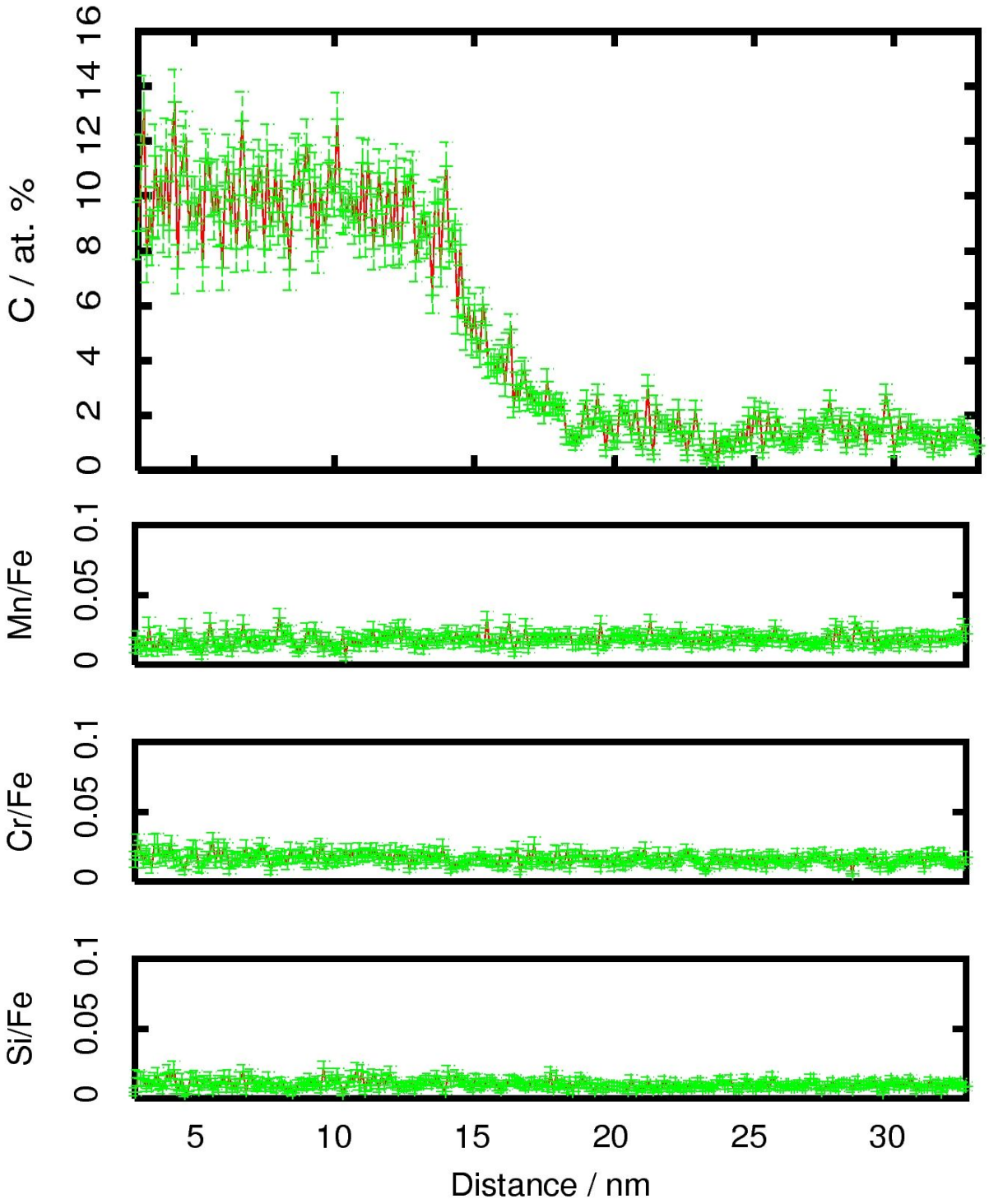


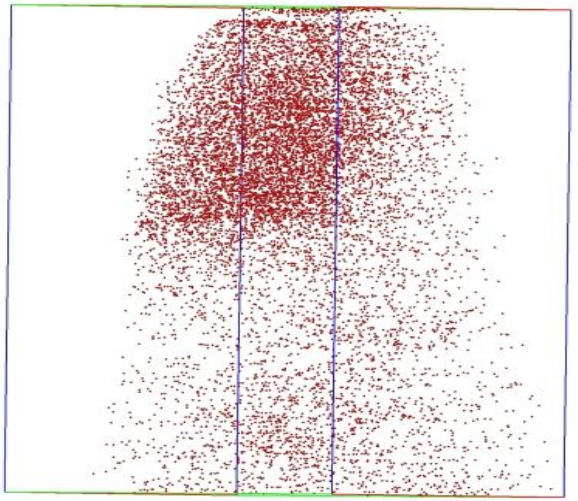






Substitutional / Solvent atom ratio constant between ferrite and austenite

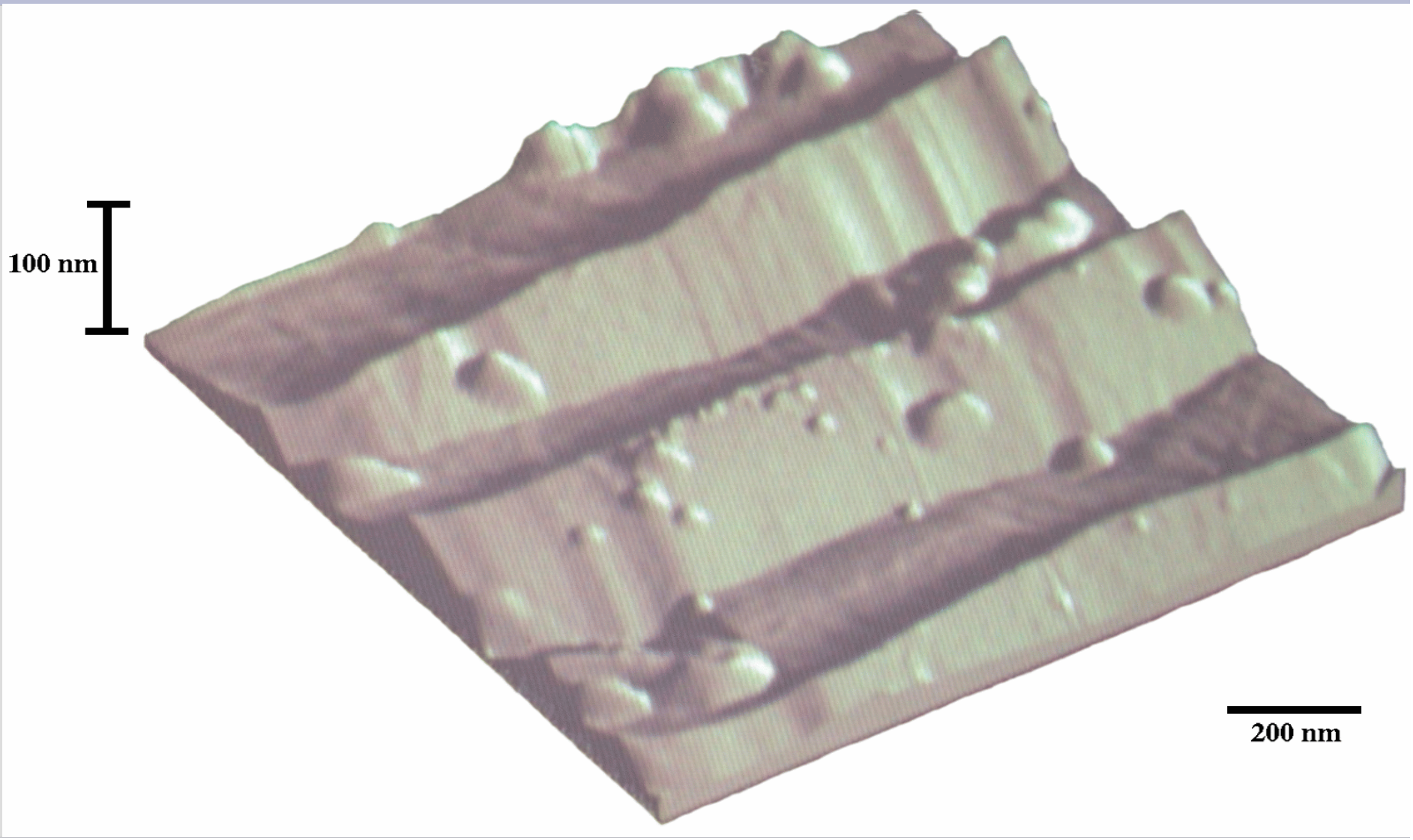




Carbon concentration;
10 at% in Austenite
1.5 at% in ferrite

Uniform substitutional solute distribution

As expected for displacive transformation

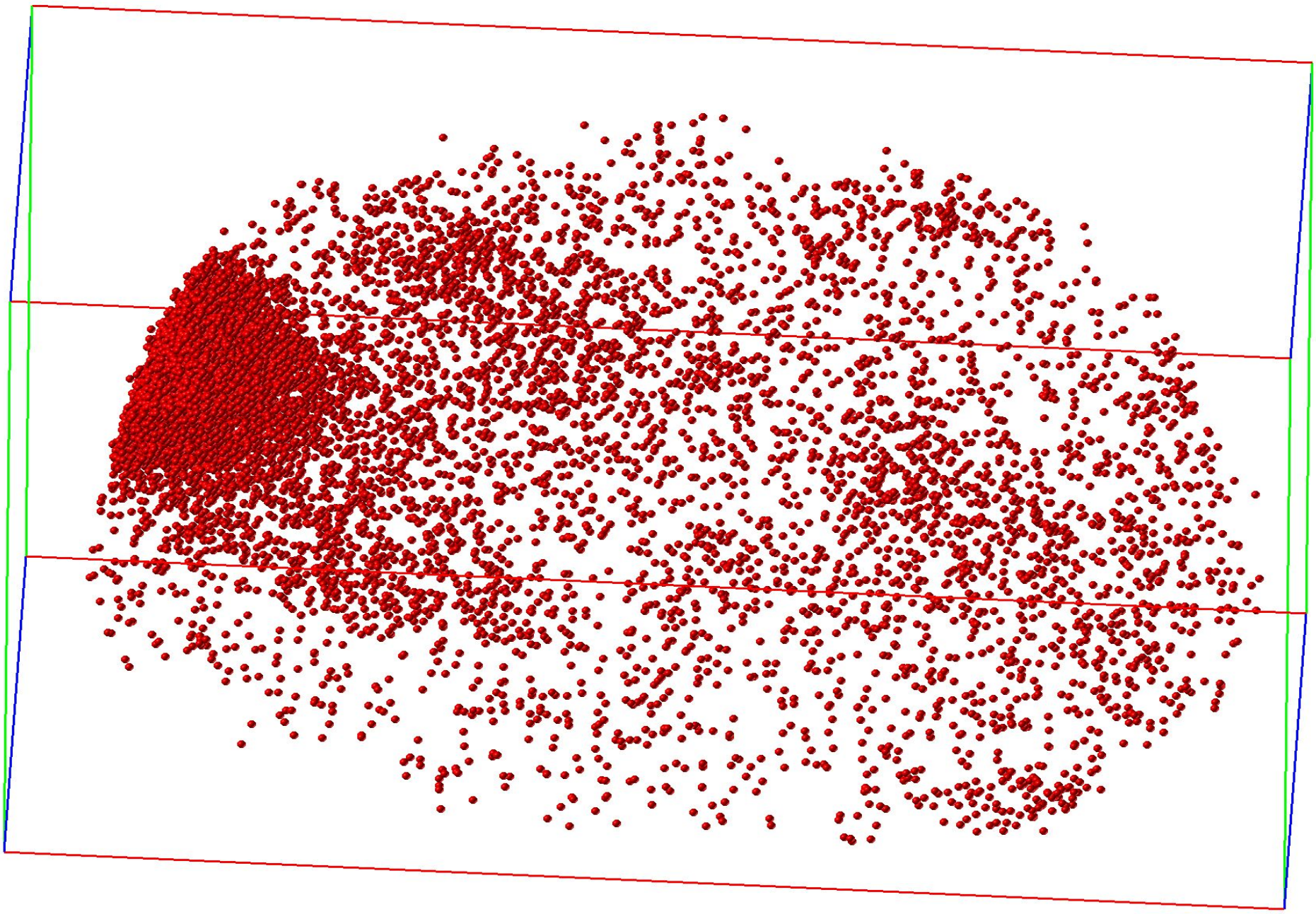


Previous Studies

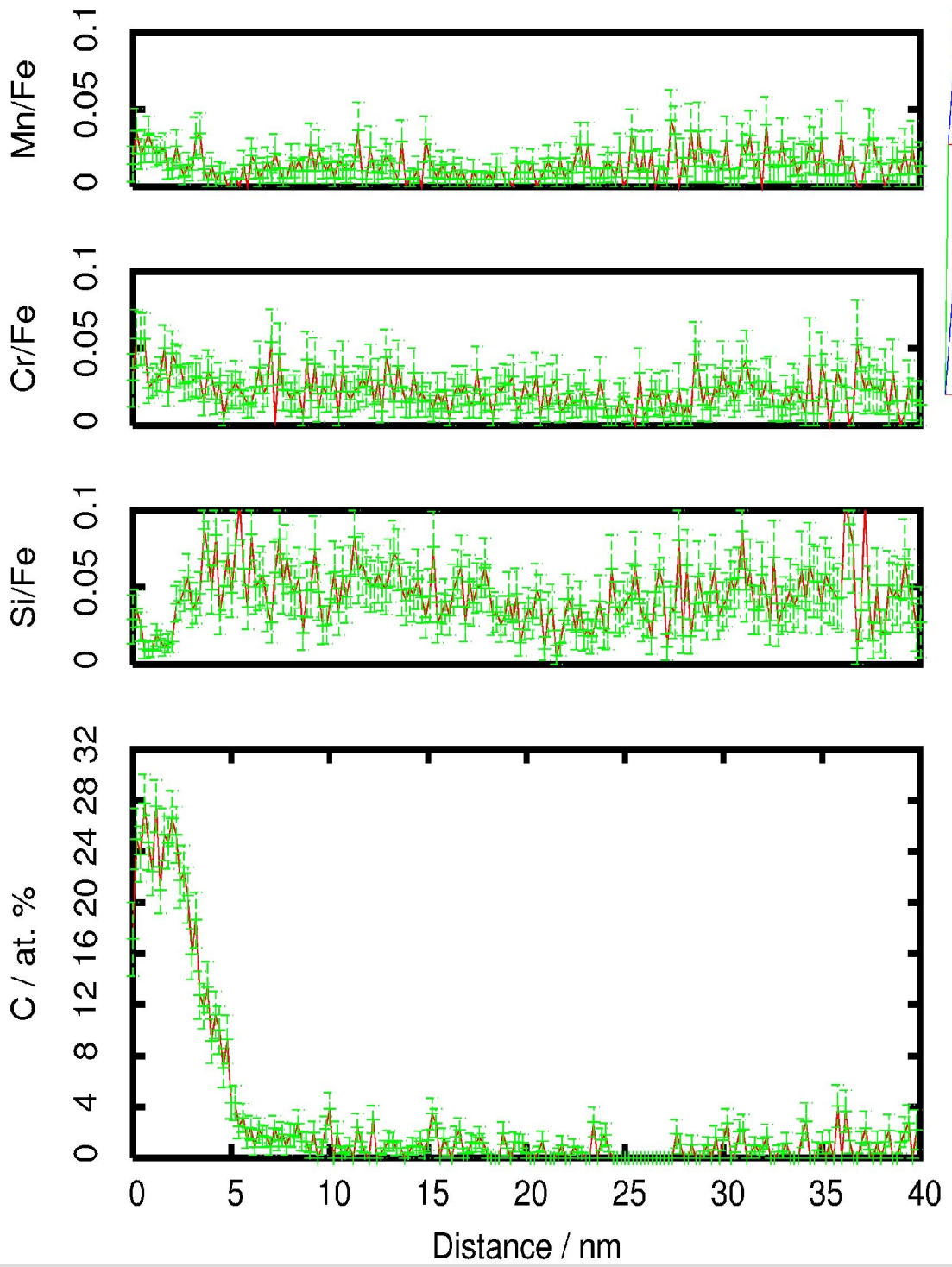
Nothing new about finding excess carbon in ferrite!

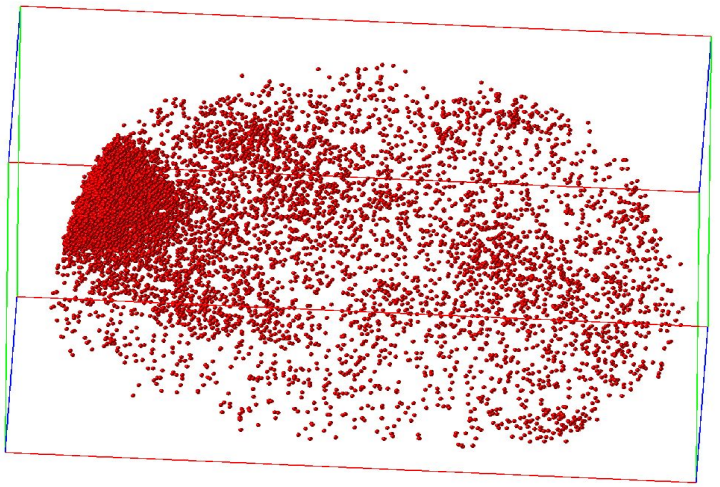
Waugh and Bhadeshia (81,82) – atom probe
Self *et al.* (80) – lattice imaging
Stark *et al.* (90) – atom-probe

Persistance of carbon in ferrite is original contribution, verified by X-ray and atom probe.



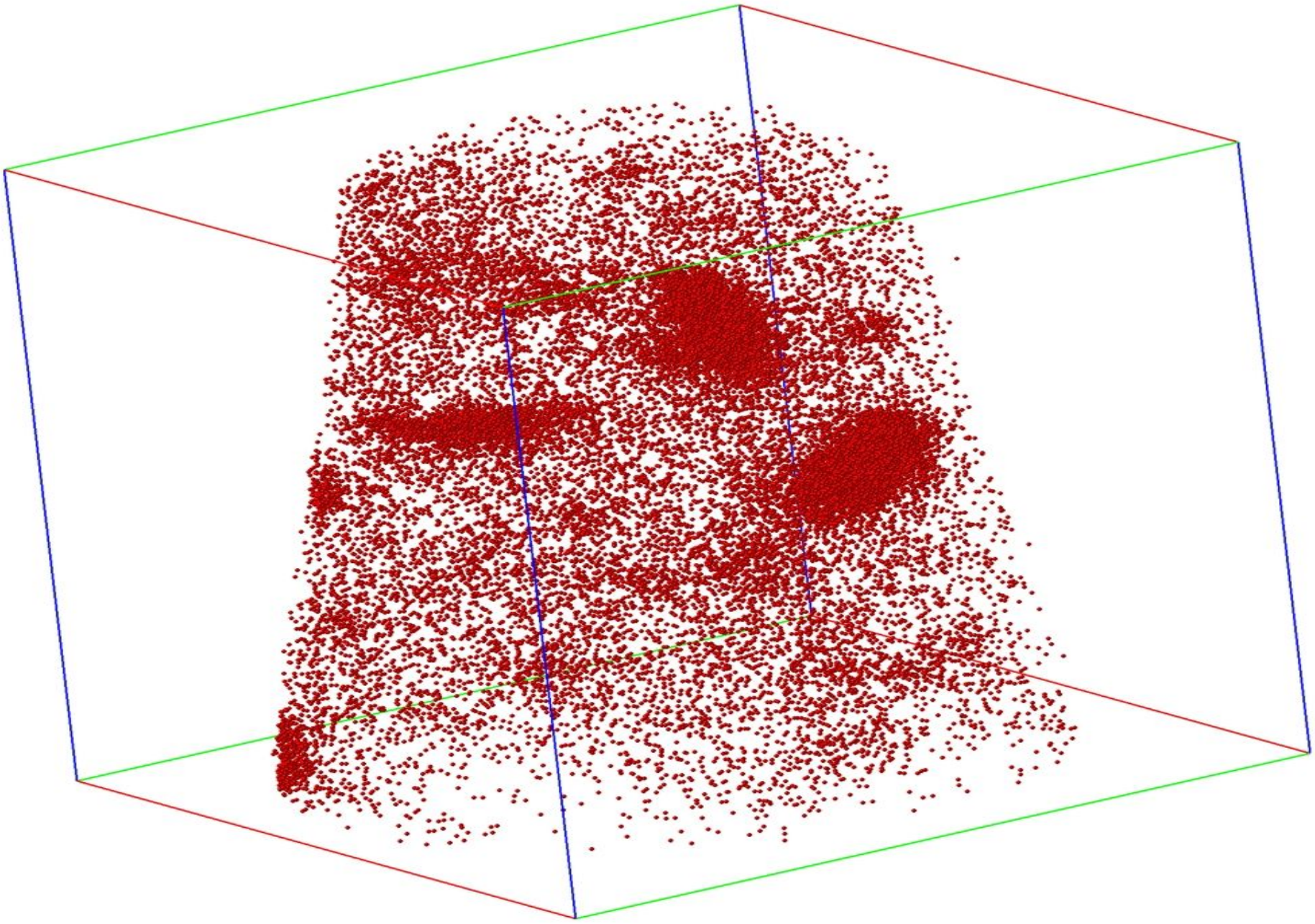
Carbon Atom Map after temper for 30 mins at 400°C



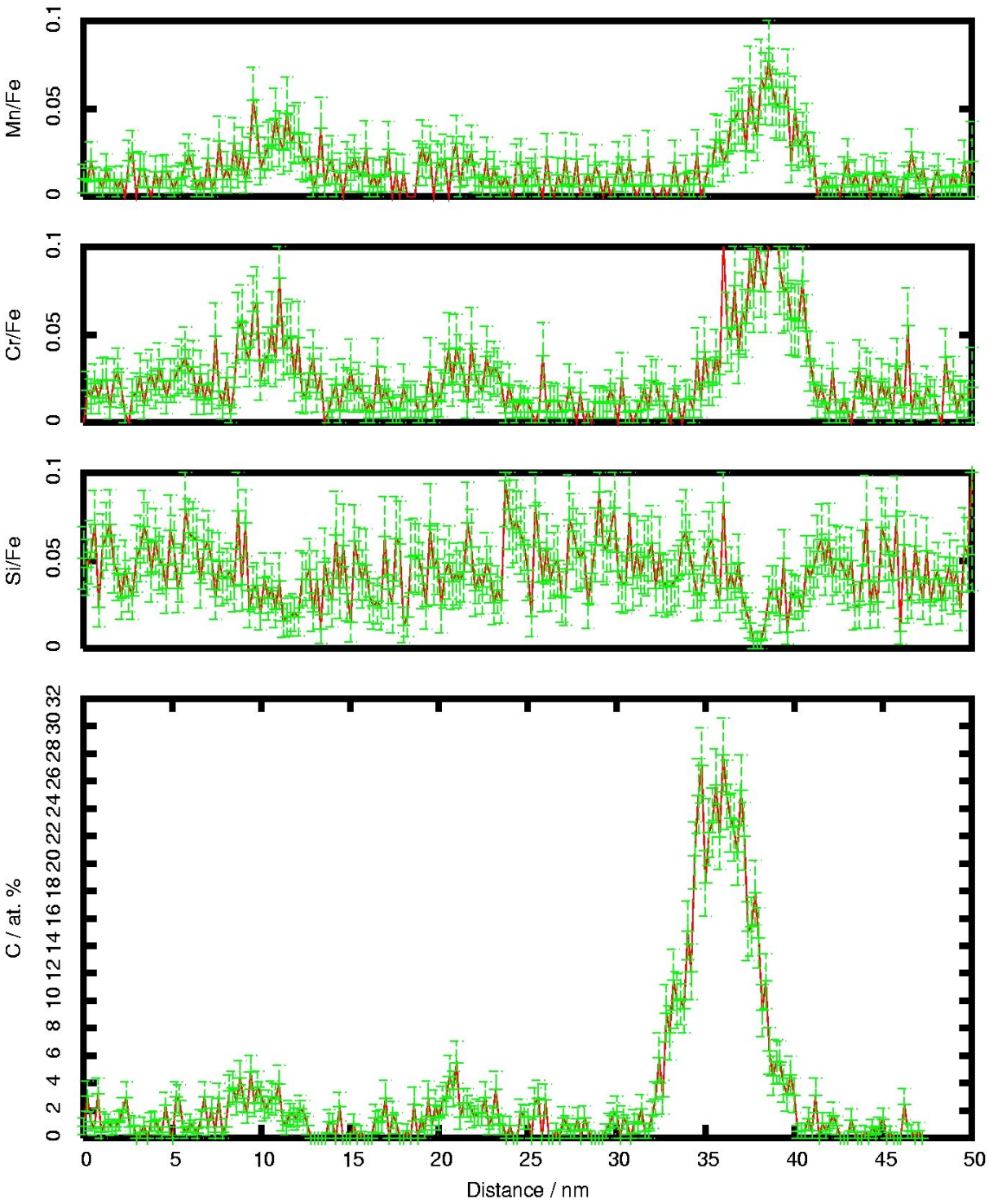


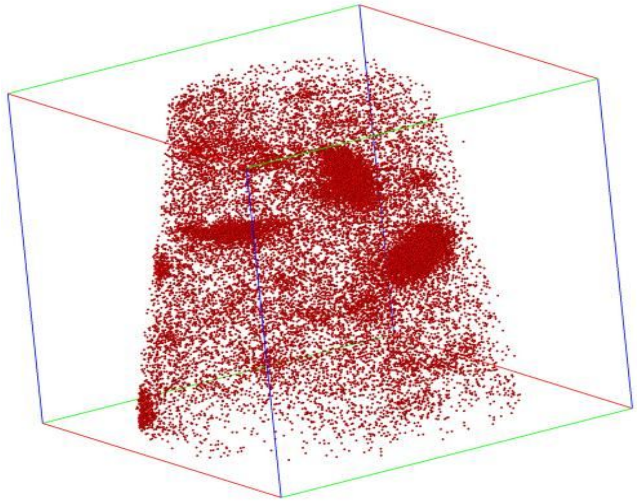
Concentration profiles, low temperature bainite tempered for 30 mins at 400°C

Ferrite ~2 at% C



Carbon atom map after tempering 30 mins at 500°C





Concentration profiles tor low temperature bainite tempered for 30 mins at 500°C

Ferrite ~1 at% C

Conclusions

Ferrite transforms without diffusion.

a large supersaturation of carbon in ferrite.

Partitions to austenite thin films, to extent slightly greater than T_o value.

X-ray concentrations consistent with atom probe.

Excess carbon trapped at defects, therefore hessitant to precipitate.

Minute iron carbides cause hardening.

Secondary hardening due to cementite!
(carbon concentrated into austenite, and then dumped at the ferrite boundaries)

Carbides prevent plates from recrystallising.

Thank you

I thank the EPSRC, CORUS, The Worshipful Company of Ironmongers and the ShaRE user centre at Oak Ridge National Laboratory for supporting this research.

Perhaps I should also thank Mike Miller, Suresh Babu, and Harry Bhadeshia for their help and enthusiasm.