Atomic Structure of Superbainite

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GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

CSIC

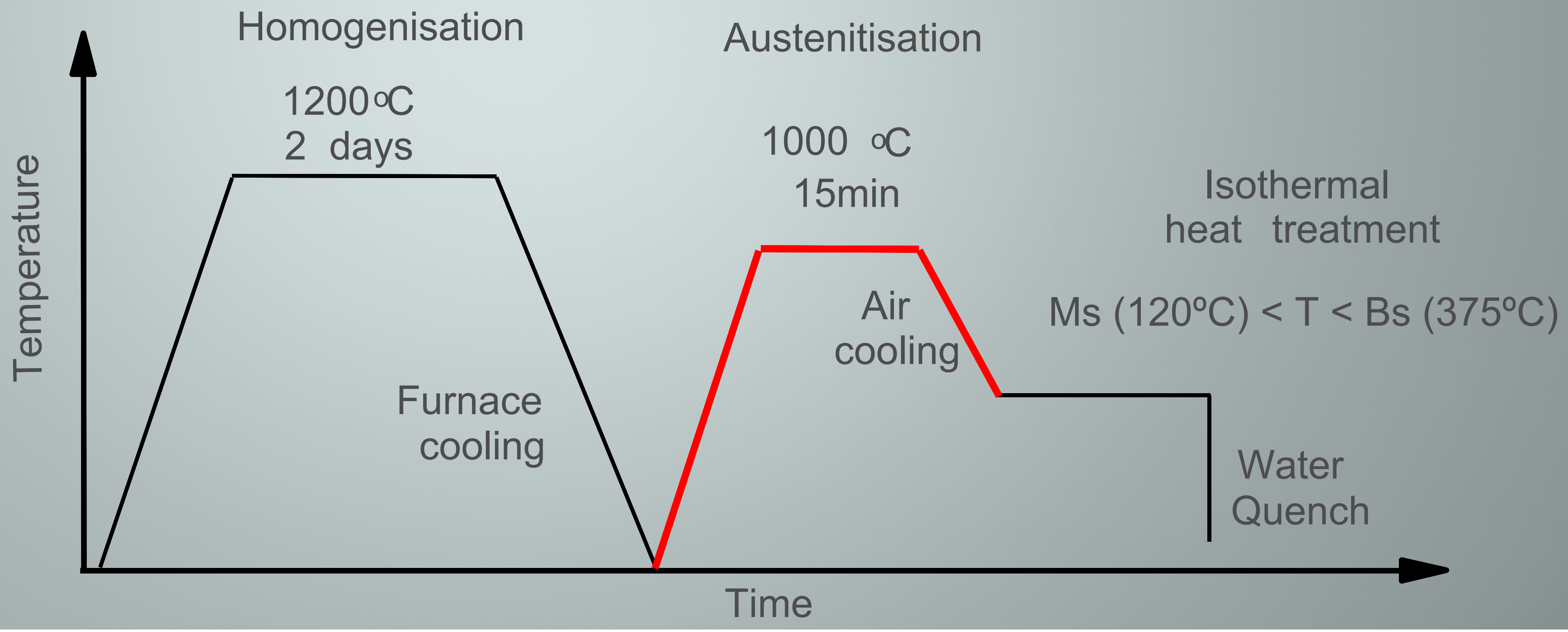
CENTRO NACIONAL DE INVESTIGACIONES METALÚRGICAS (CENIM)

Driving force for this work

1st Generation of Superbainite was born (1999-2000) at Cambridge Univ.

Chemical composition.

	C	Si	Mn	Mo	Cr	V
Wt-%	0.98	1.46	1.89	0.26	1.26	0.09
At. %	4.34	2.76	1.82	0.14	1.28	0.09

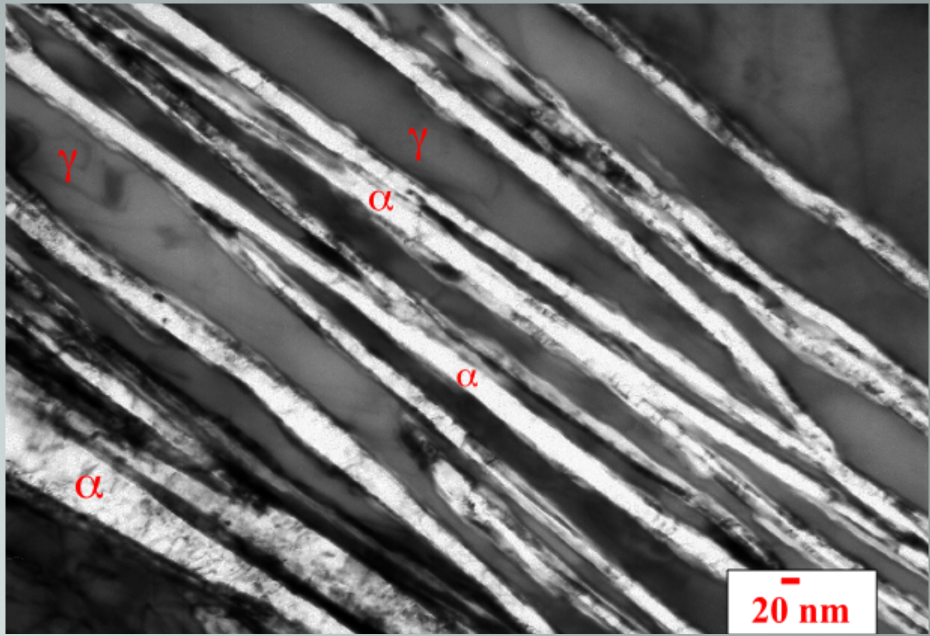


Some microstructural facts

Nano bainitic ferrite plates (up to 80%) & retained austenite

<u>no cementite</u>

Development of Hard Bainite, ISIJ Internacional, Vol 43, No8, (2003), 1238-1243.

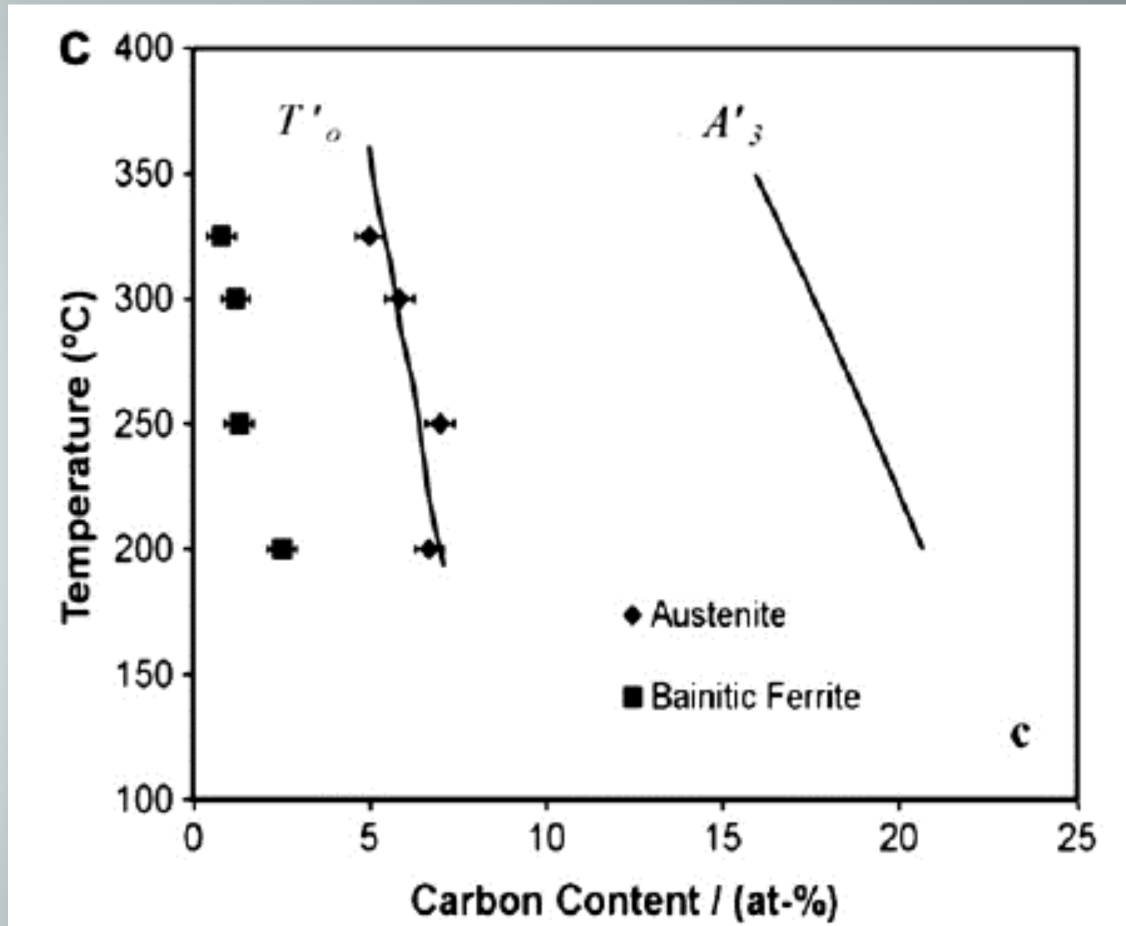


200ºC

250ºC

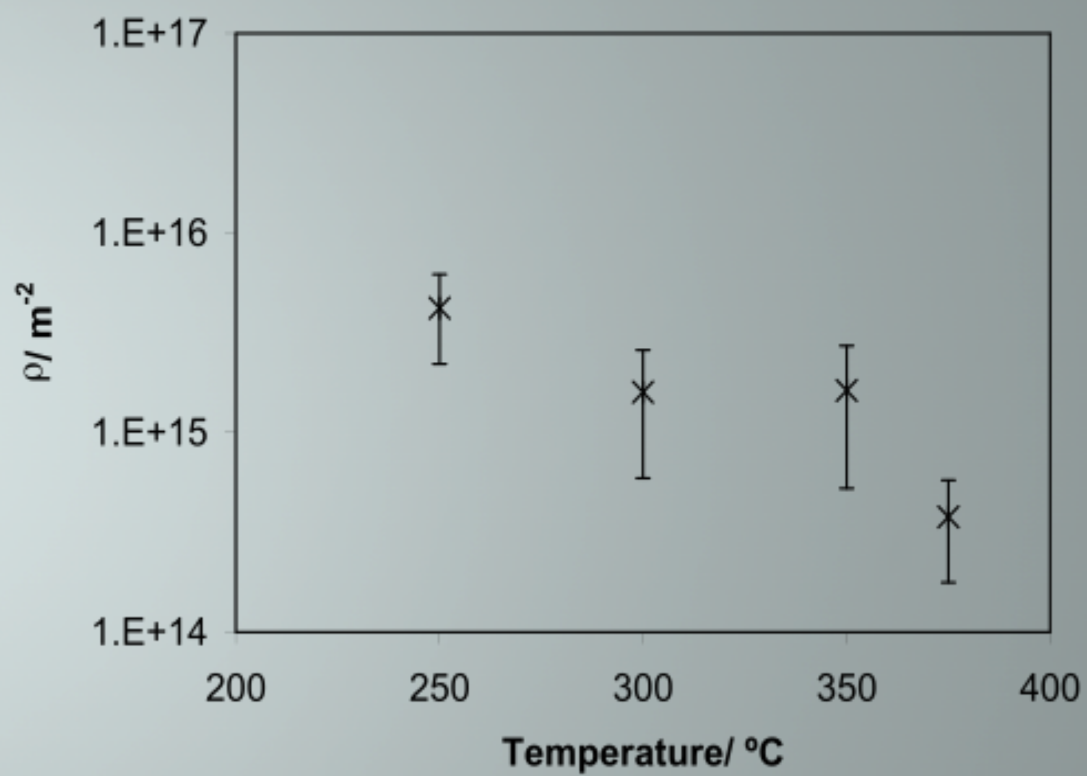
Fact

Ferrite and Austenite are C enriched

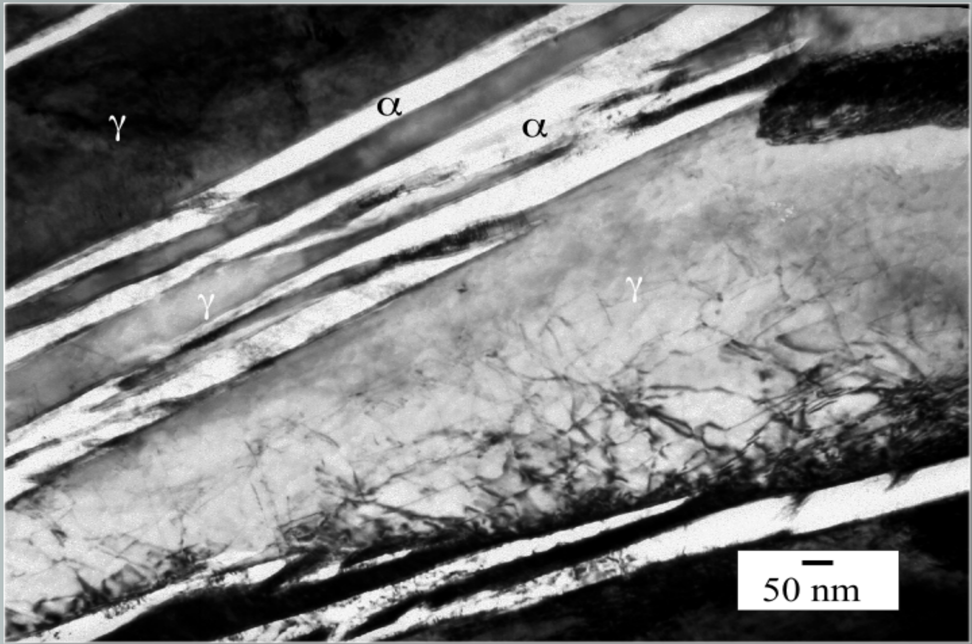


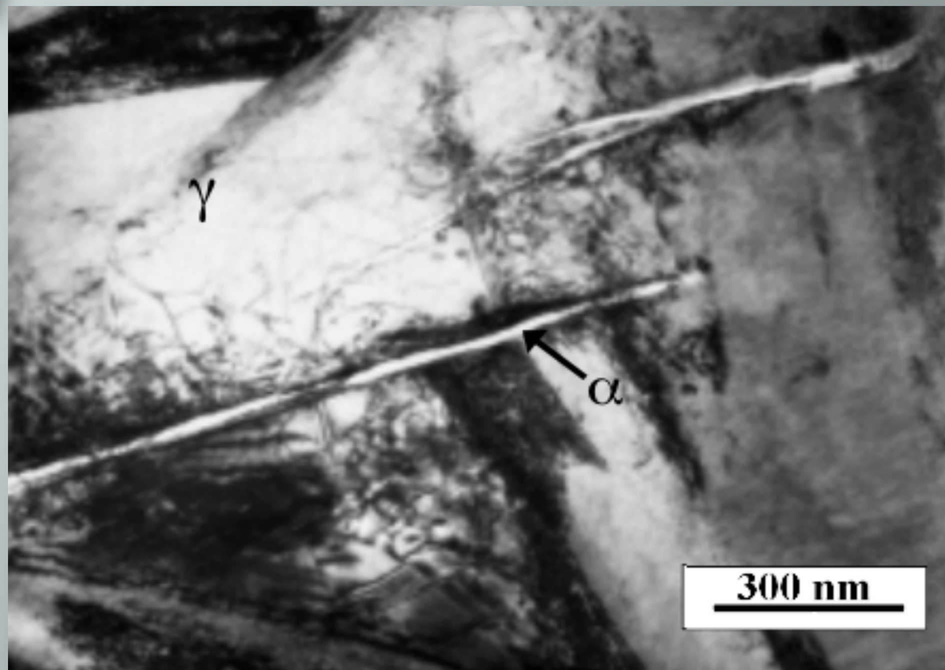
Fact
Highly dislocated

Shape change accompanying diffusionless growth is plastically accommodated causing the accumulation of dislocations, increasing in number as transformation temperature decreases .

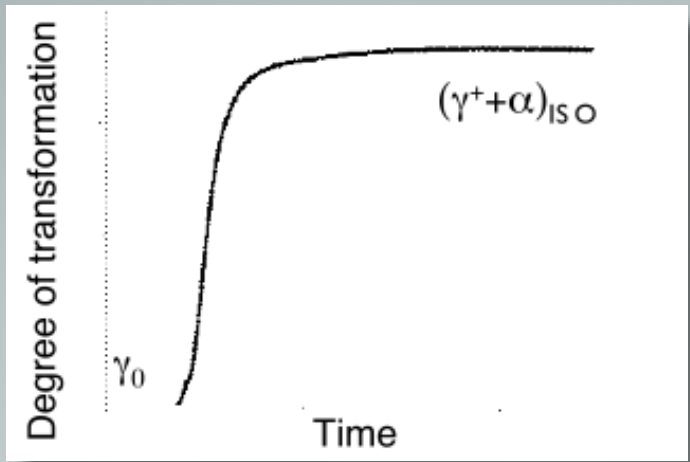


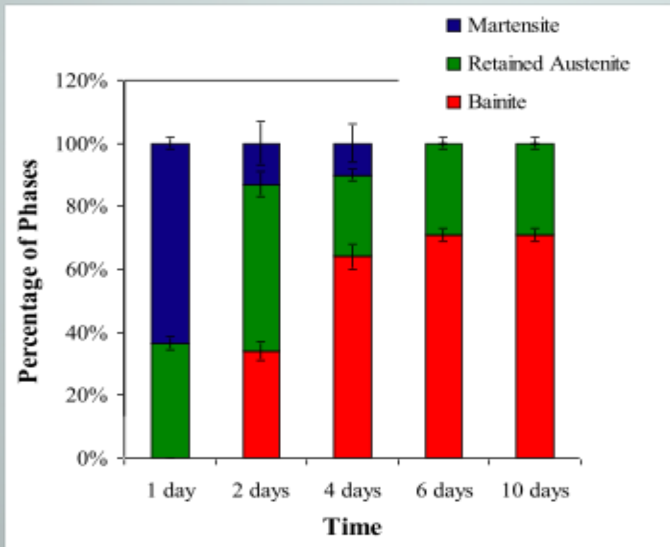
- H.K.D.H. Bhadeshia and D.V. Edmonds Metall. Trans. 10A (1979) 895-907
- C. Garcia-Mateo and F.G. Caballero, ISIJ Int. 45 (2005) 1736
- C. Garcia-Mateo, F. G .Caballero, et al Scripta Materialia 61 (2009) 855

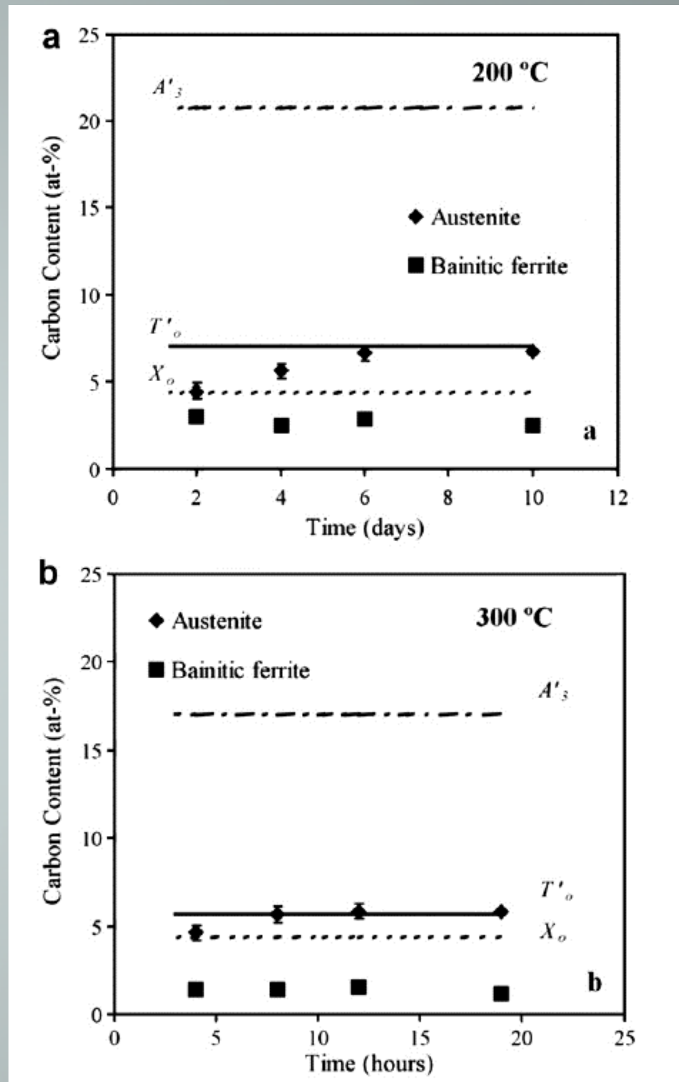

α
α
γ
γ
γ
50 nm


γ
α
300 nm

Peculiarities needing further research





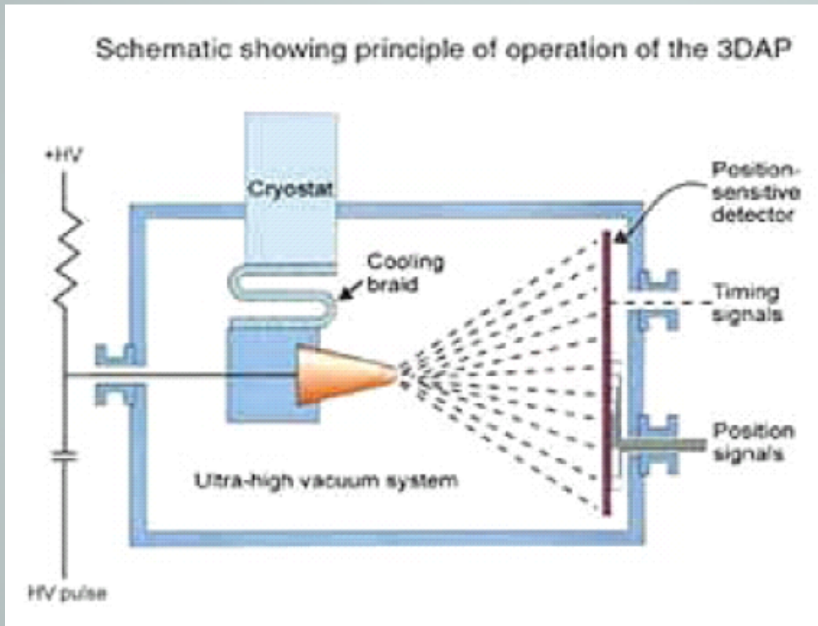


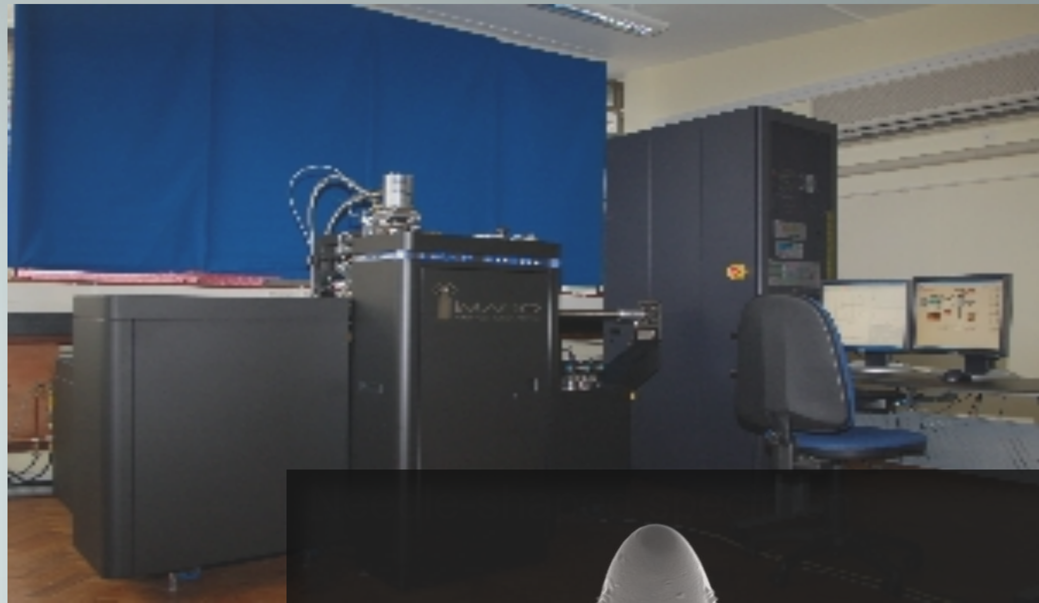
X-ray

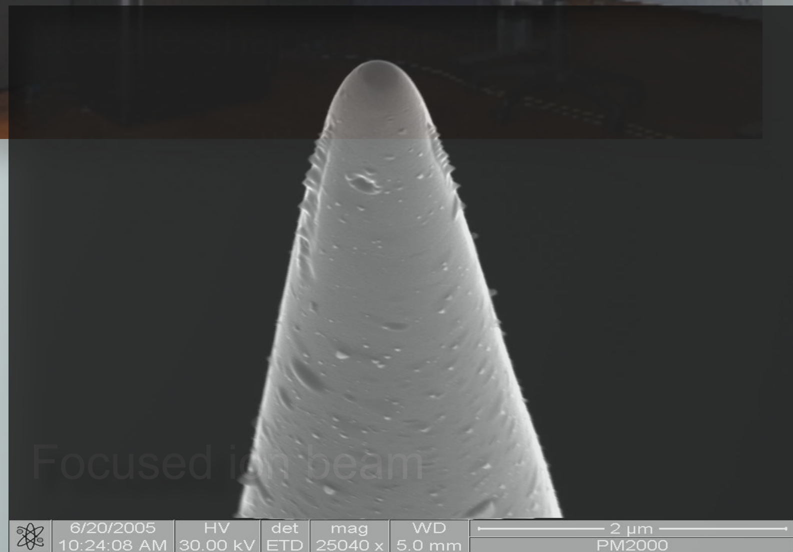
C content in ferrite is 10 times higher than that expected from paraequilibrium (α+γ) i.e 0.12 at.%

Still no cementite was observed within bainitic ferrite plates

Atom Probe Tomography (APT)

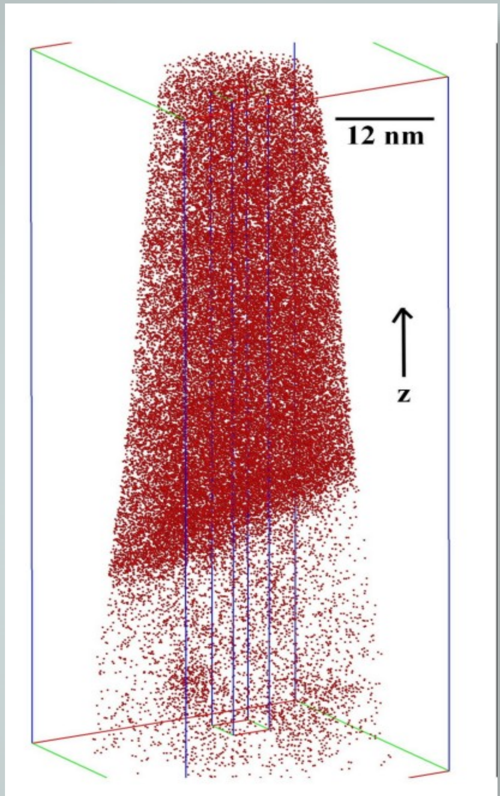


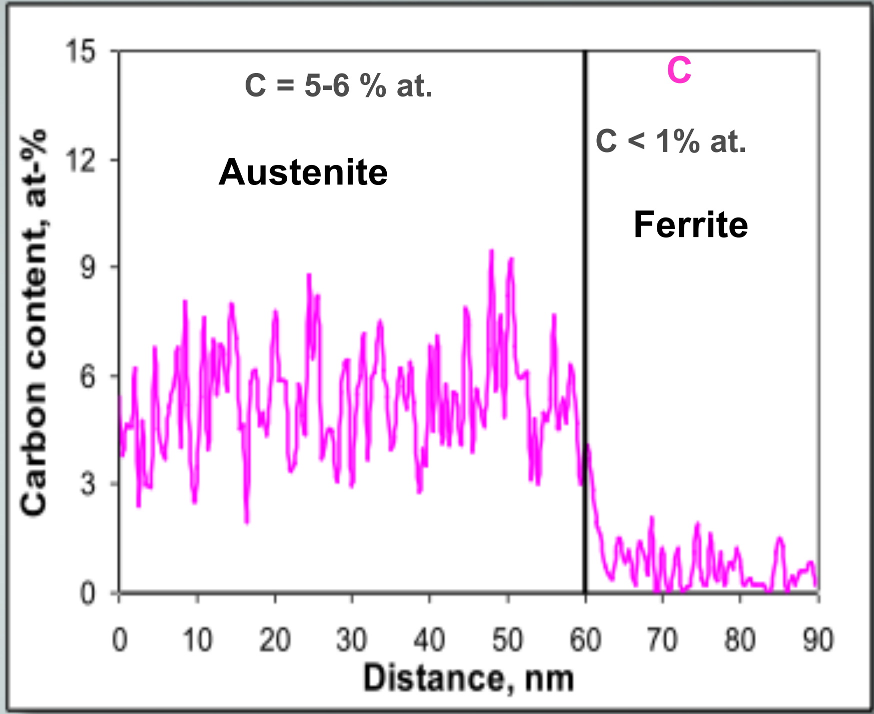


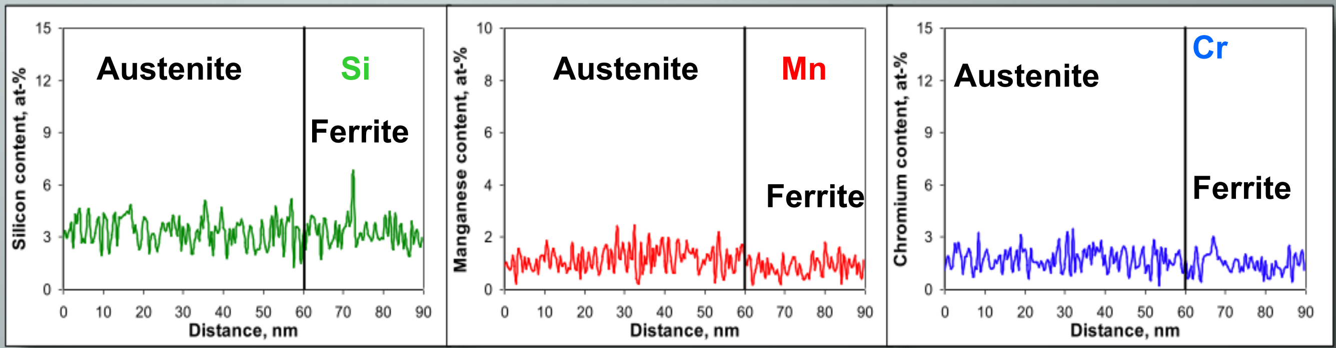


3D picture of the atom distribution is built up.

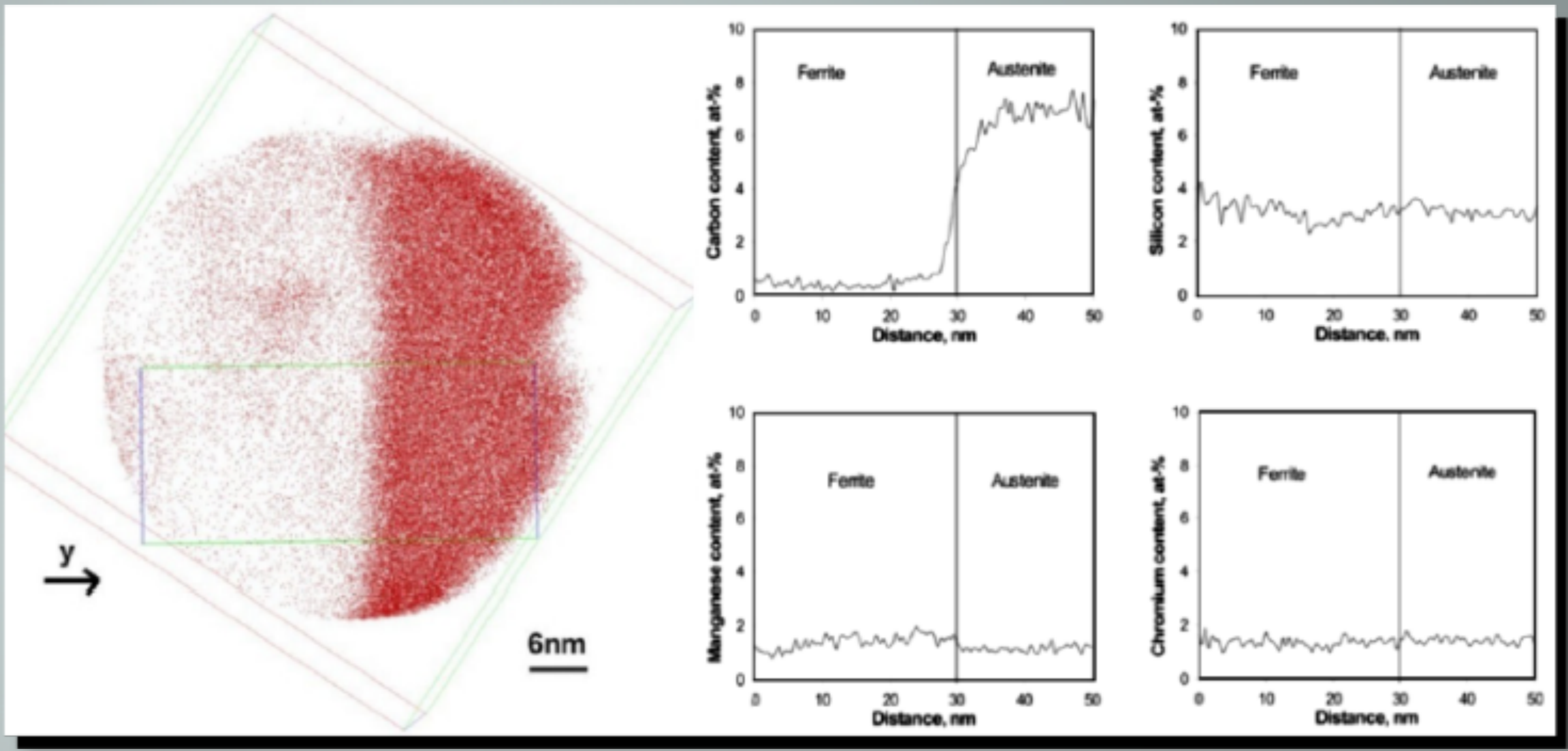
200 ºC for 6 days, carbon atom map 5% at.







300 ºC for 8h



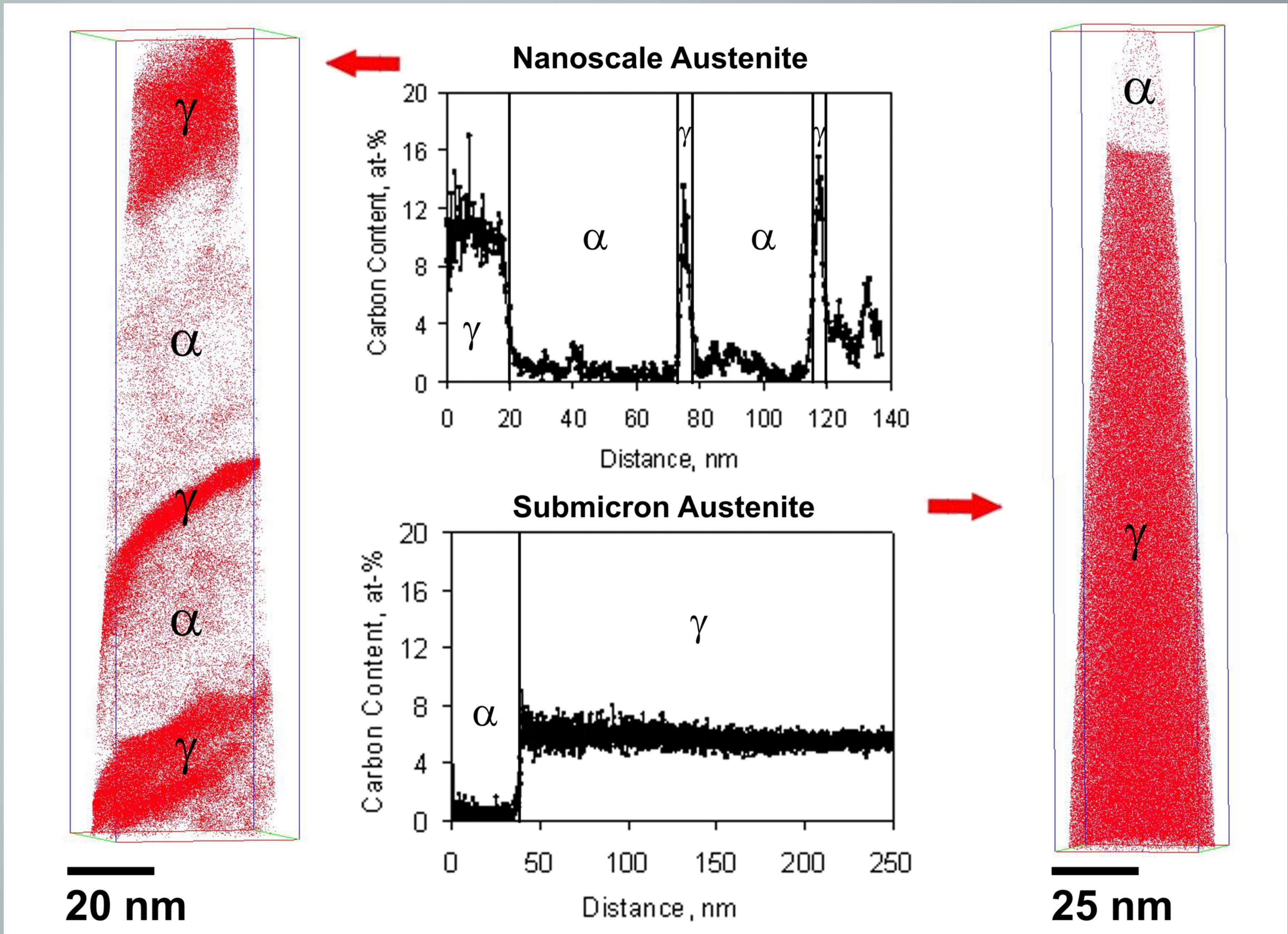
Only C changes within phases

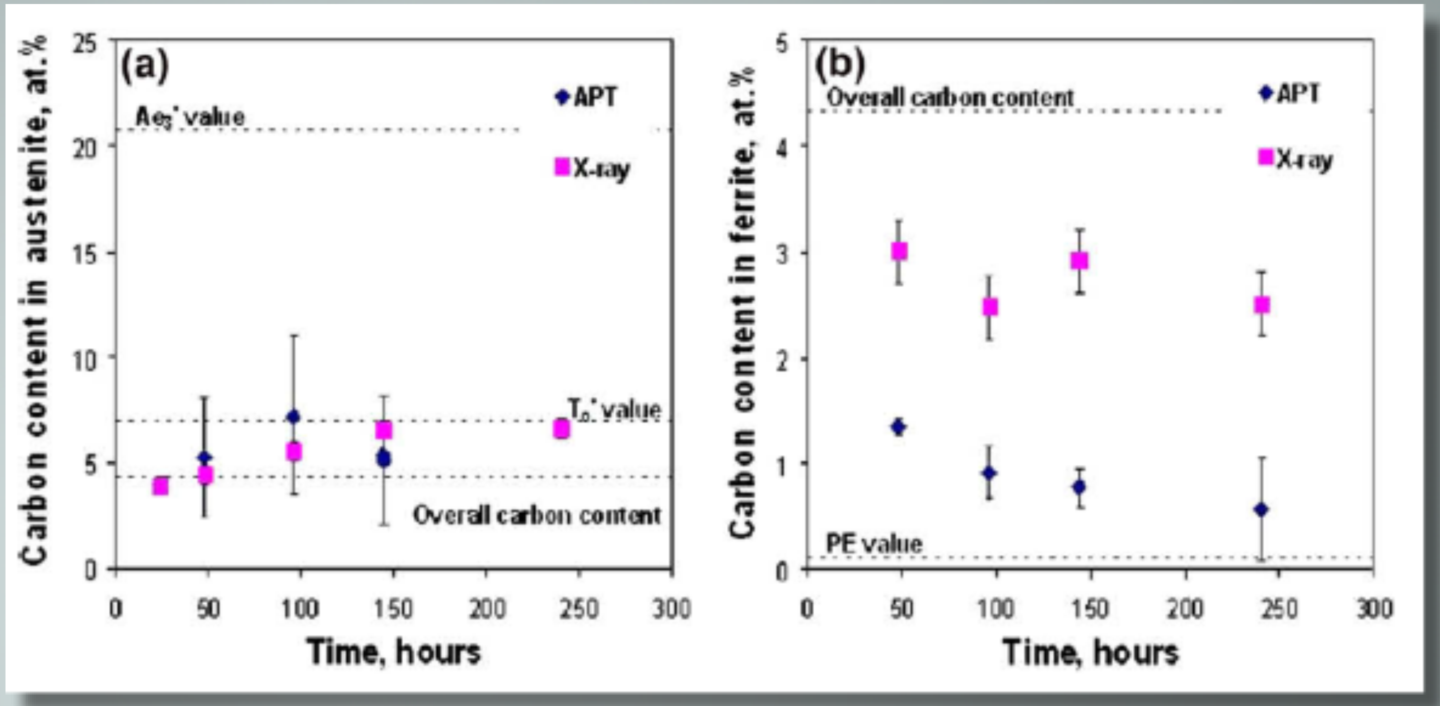
There is no segregation to the α−γ interface

(As originally observed by Bhadeshia HKDH, Waugh AR. Acta Metall 1982;30:775)

Additional proof of the displacive nature of bainite transformation

Heterogeneous distribution of carbon in austenite





- High level of carbon in bainitic ferrite, well beyond that expected from para-equilibrium with austenite (0.12at.% C)….and NO precipitation !!

- The atom-probe results also indicated that the amount of carbon in bainitic ferrite increased as the transformation temperature decreased.

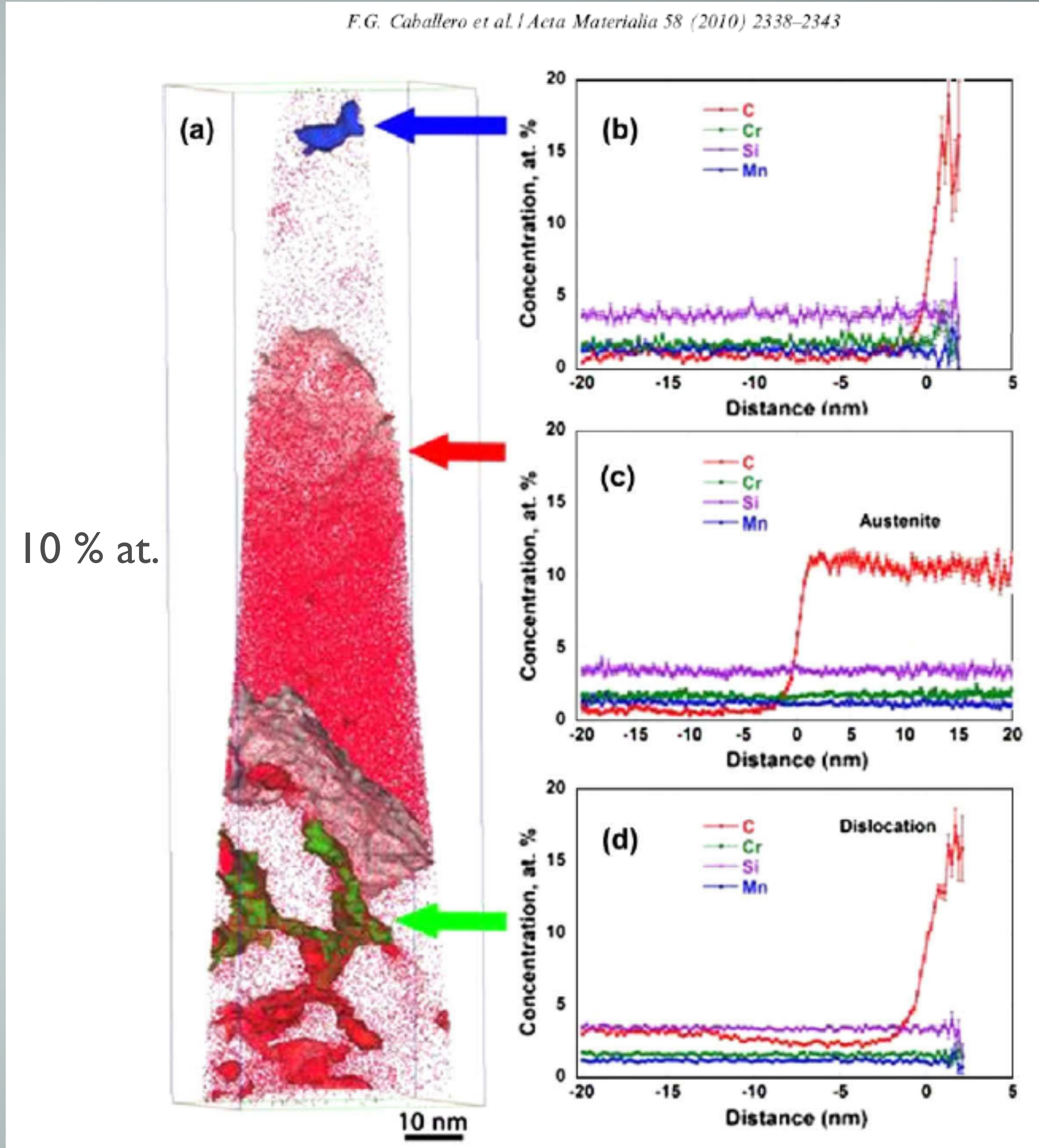
C is found also

As Carbon Cluster*
15 %at.

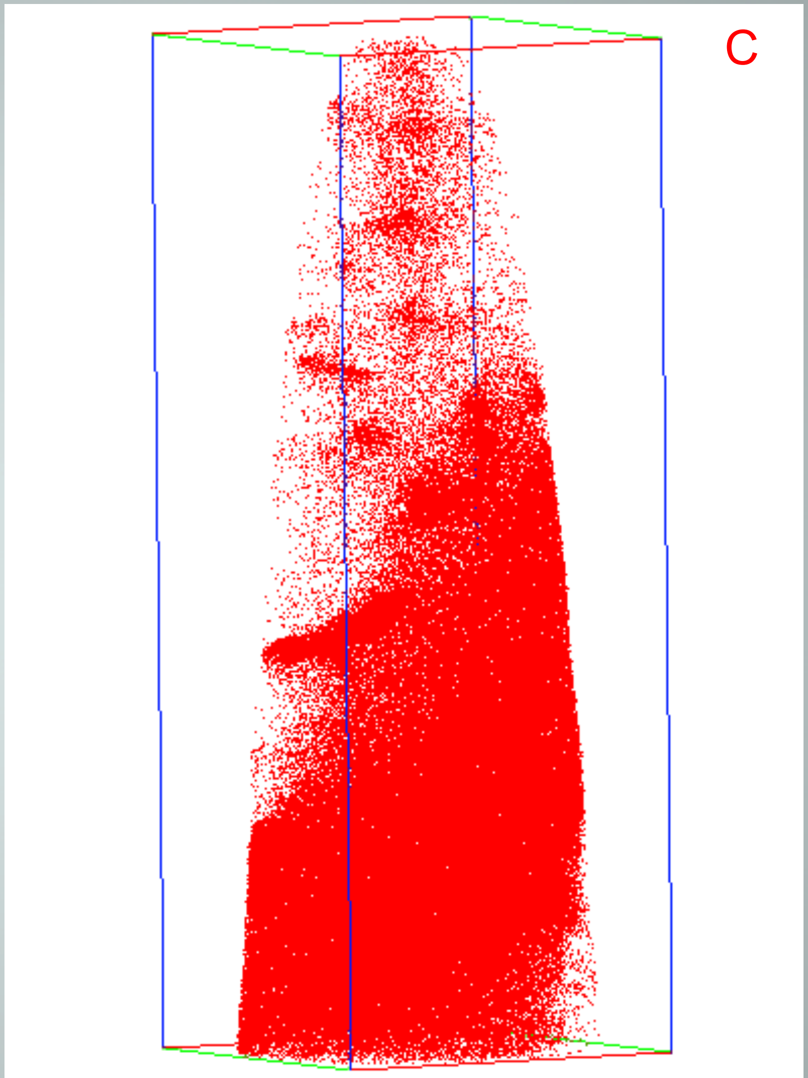
Trapped at dislocations
Cottrell atmospheres
7.4 to 13.4 % at.

* shows a maximum carbon content of 15 at.%, higher than that associated with dislocations, but with Cr and Mn % too low (less than 2 at.%) to be identified as a carbide.

10 % at.



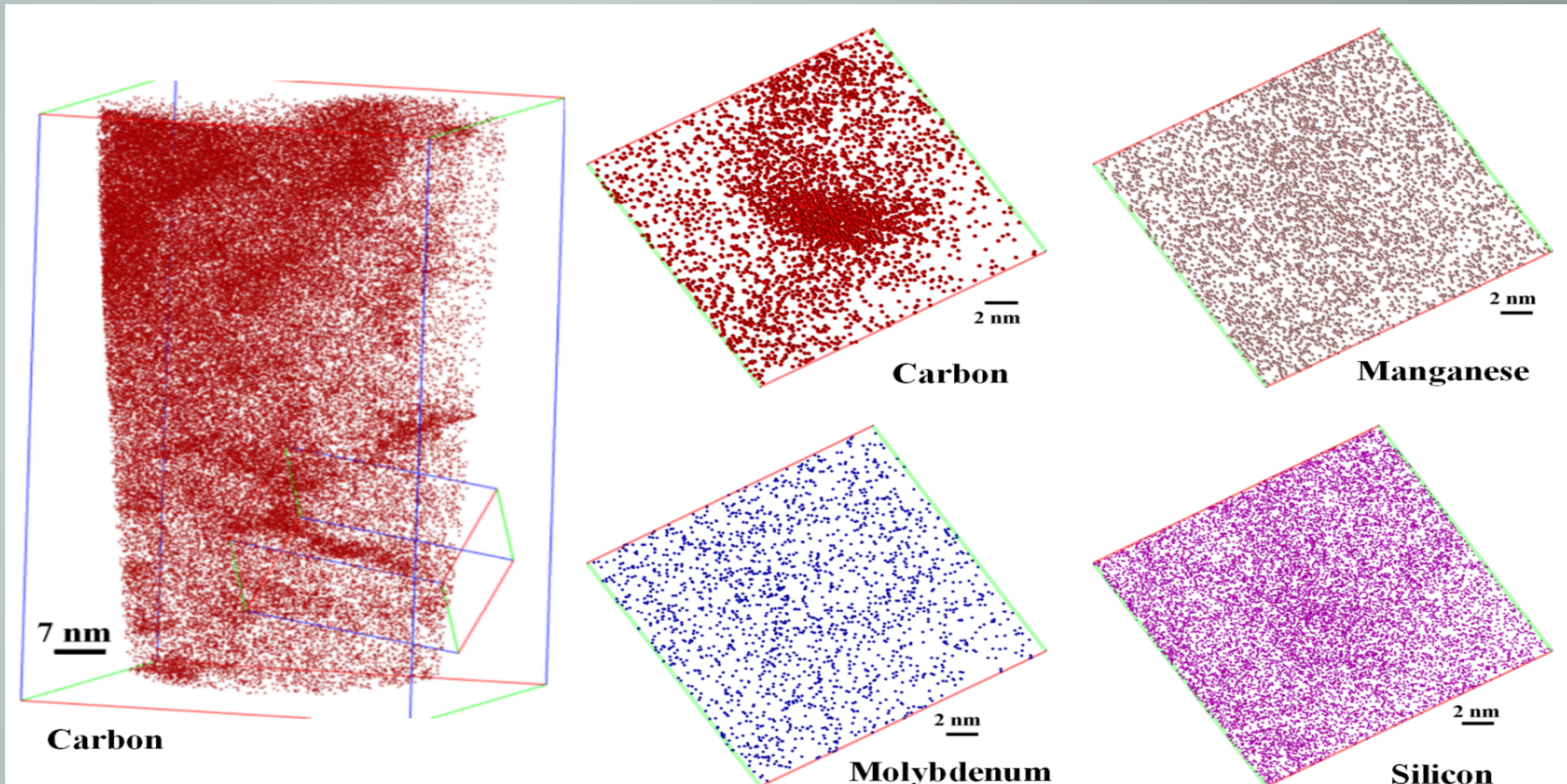
Dislocations at the Atomic Scale



51x51x140 nm

200 ºC for 2 days

Dislocations at the Atomic Scale only C diffuses to dislocations

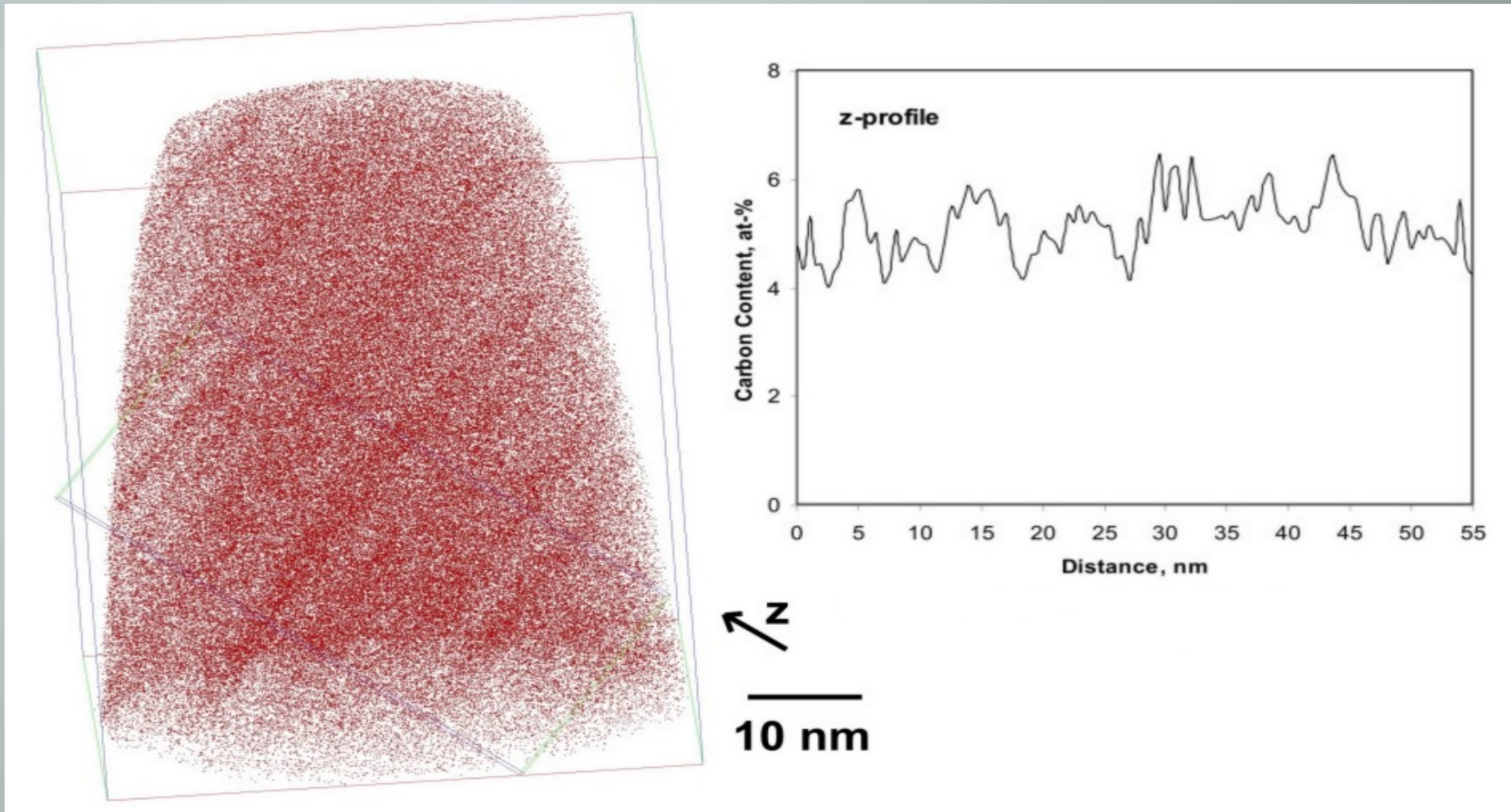


200 ºC for 2 days

C is also found segregated at microtwins in austenite

Micro-twins at the Atomic Scale

300 ºC for 3 hours



Carbon

3D APT allow to

1. Add further prove to bainite displacive character. No partitioning of elements.

2. C in bainitic ferrite is >> than that expected of $(\alpha+\gamma)_p$

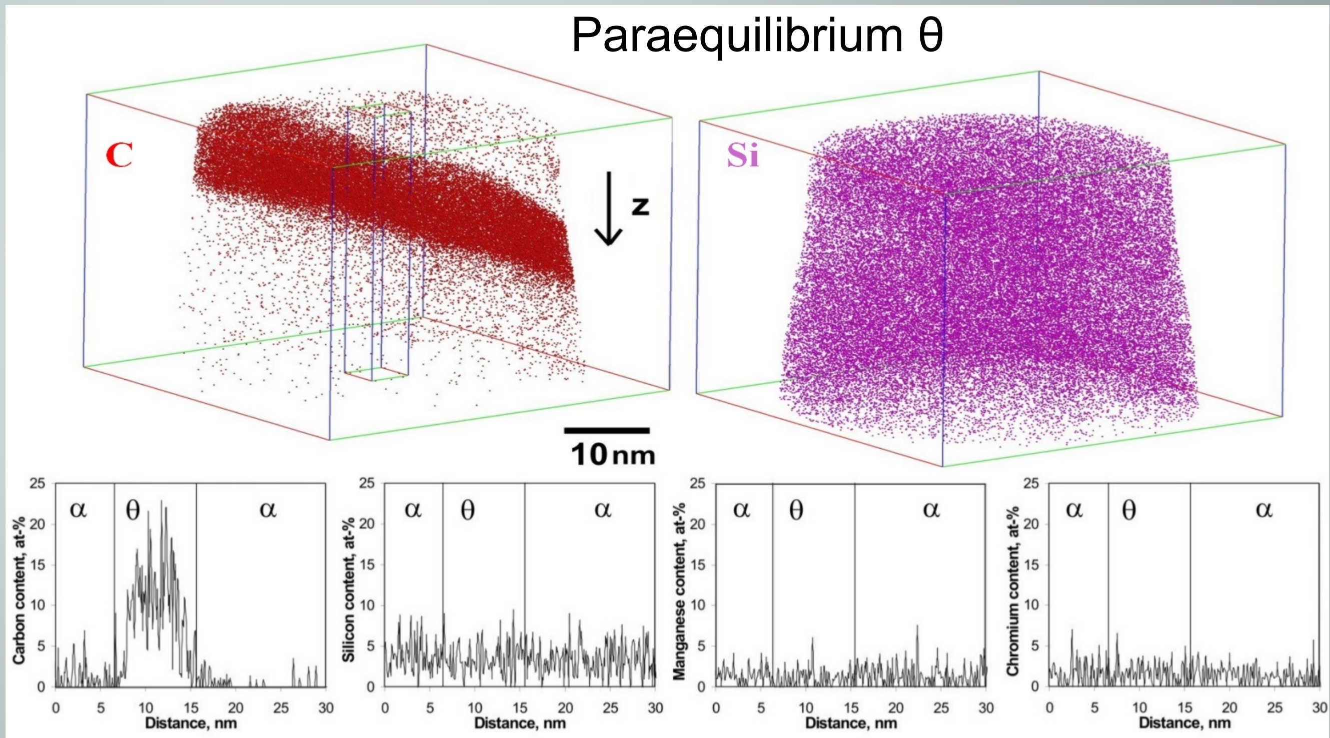
3. C is trapped at dislocations impeding its diffusion to γ after growth and also preventing precipitation

4. C gathers as cluster

5. C segregates to microtwins in austenite

3D APT allowed to uncover another interesting fact.

Initially, TEM was unable to reveal carbide particles inside bainitic ferrite, however θ and not ε-carbide was identified as the lower bainite carbide (even at early stages of transformation) despite the high carbon and high silicon content of the steel used



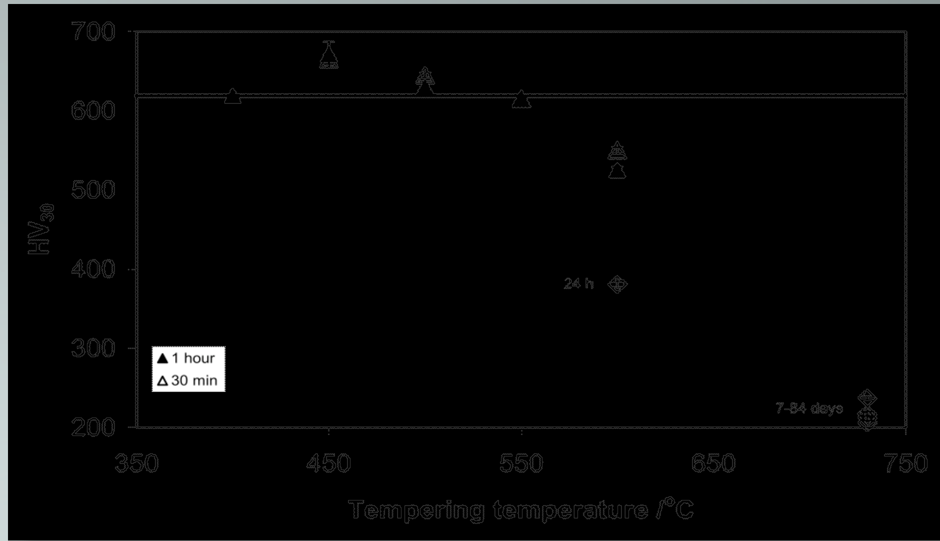
Carbon trapping at dislocations prevents the decarburization of super-saturated ferrite and, to some extent, alters the carbide precipitation sequence during low temperature bainite formation

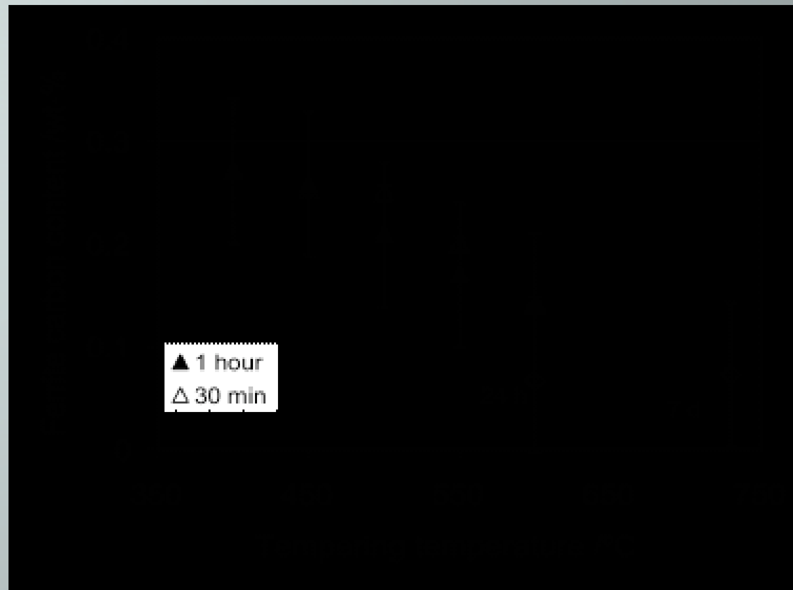
..so what is happening
during tempering of superbainitic
microstructures !!

?

Tempering resistance

200ºC microstructure
+
Time
+
Temperature

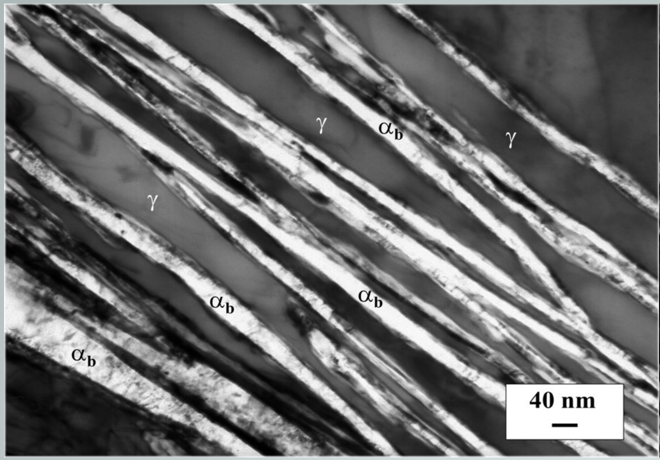




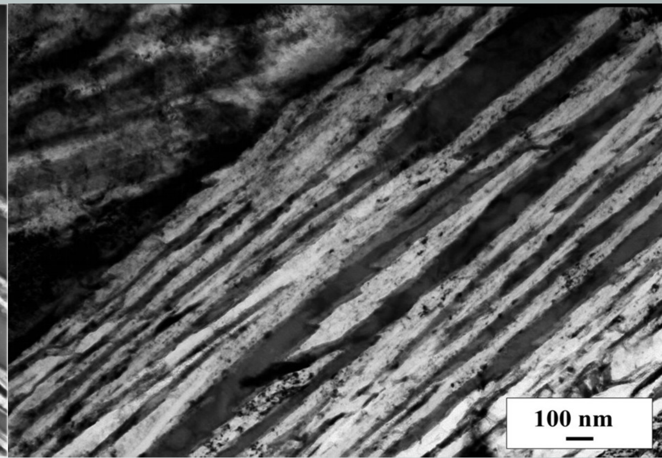
C. Garcia-Mateo, Mat. Scie. Tech., Vol. 51 (2004) 767-770

Microstructural evolution during tempering

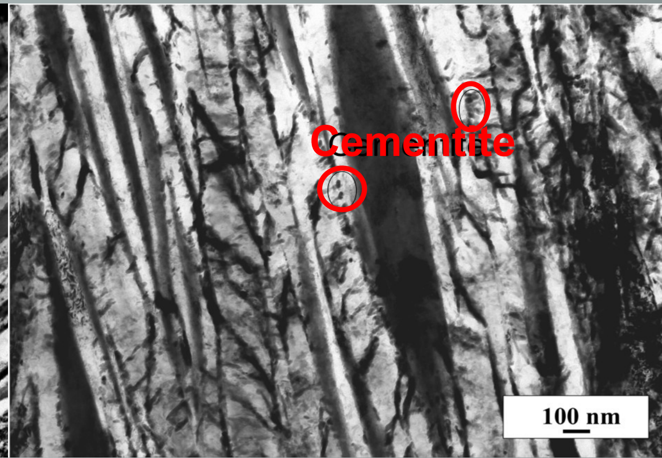
Initial microstructure



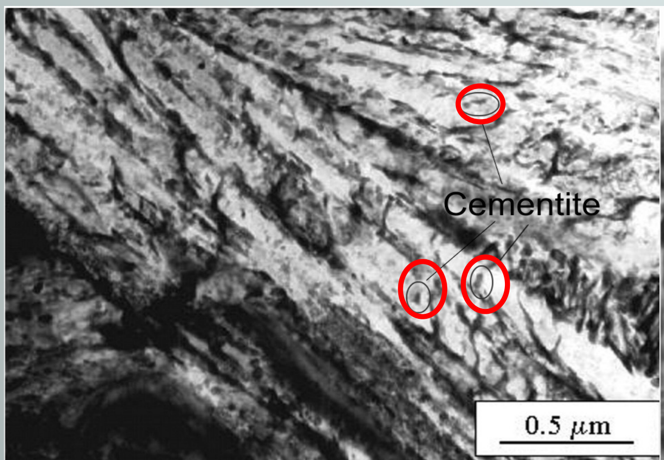
400ºC 1 hour, no apparent change



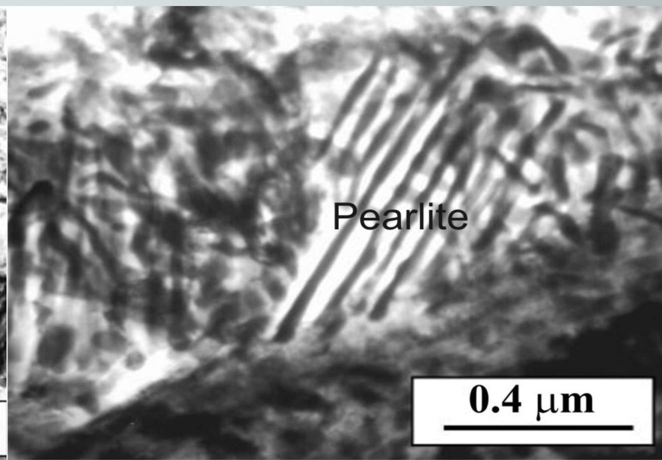
450ºC 30 min, γ → α+θ



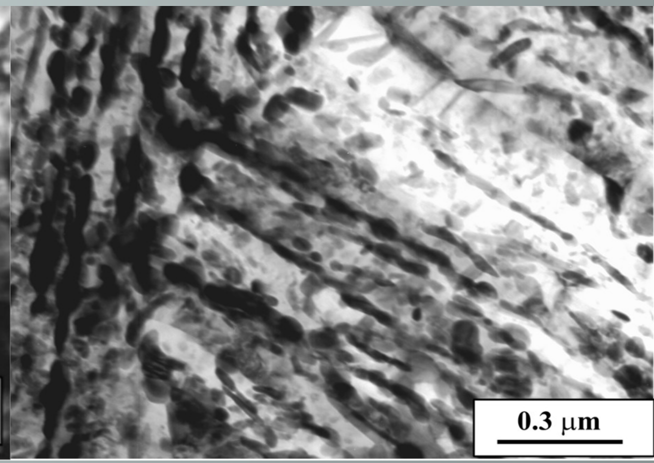
500ºC 30 min, γ → α+θ



500ºC 30 min, γ → α+θ+Pearlite

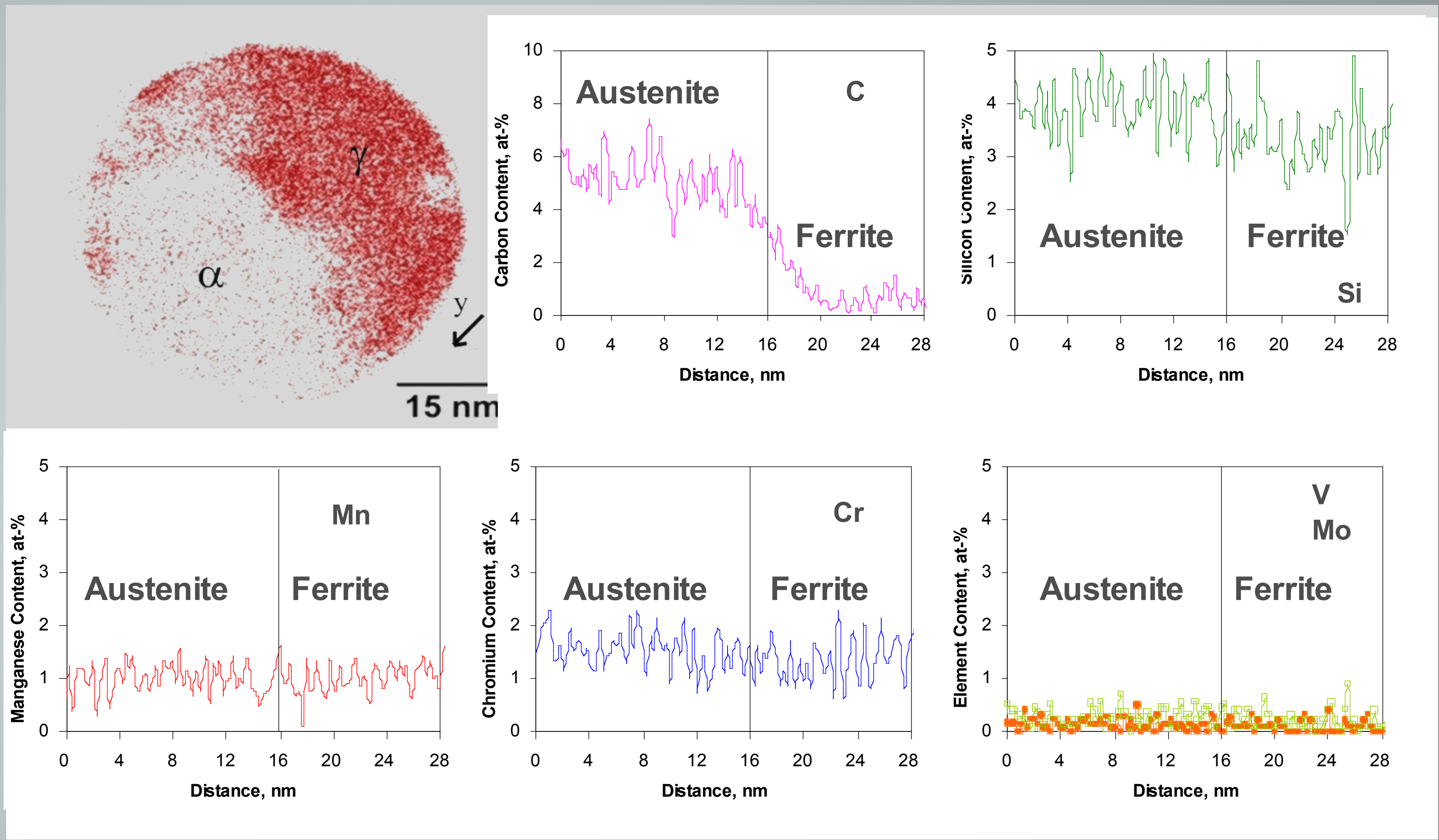


600ºC 30 min, coarsening and full recovery



500ºC to 600ºC recovery of the microstructure

400ºC for 1 h



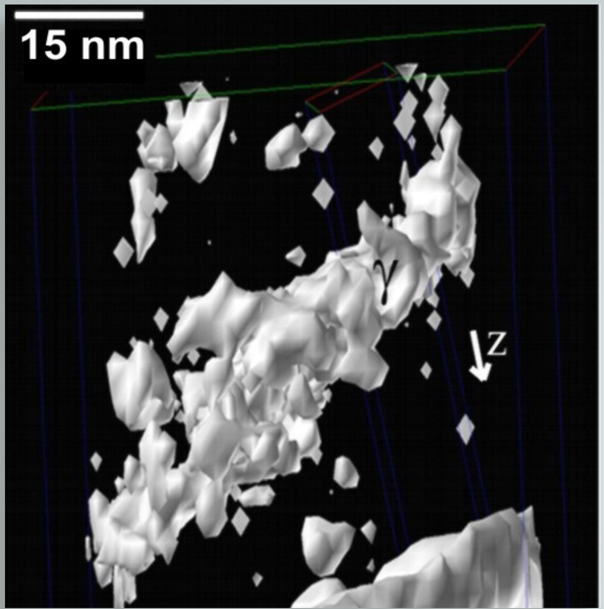
Substitutional elements are expected to redistribute as the mixture of bainitic ferrite and retained austenite is tempered

Carbon content within the phases is similar to the original microstructure

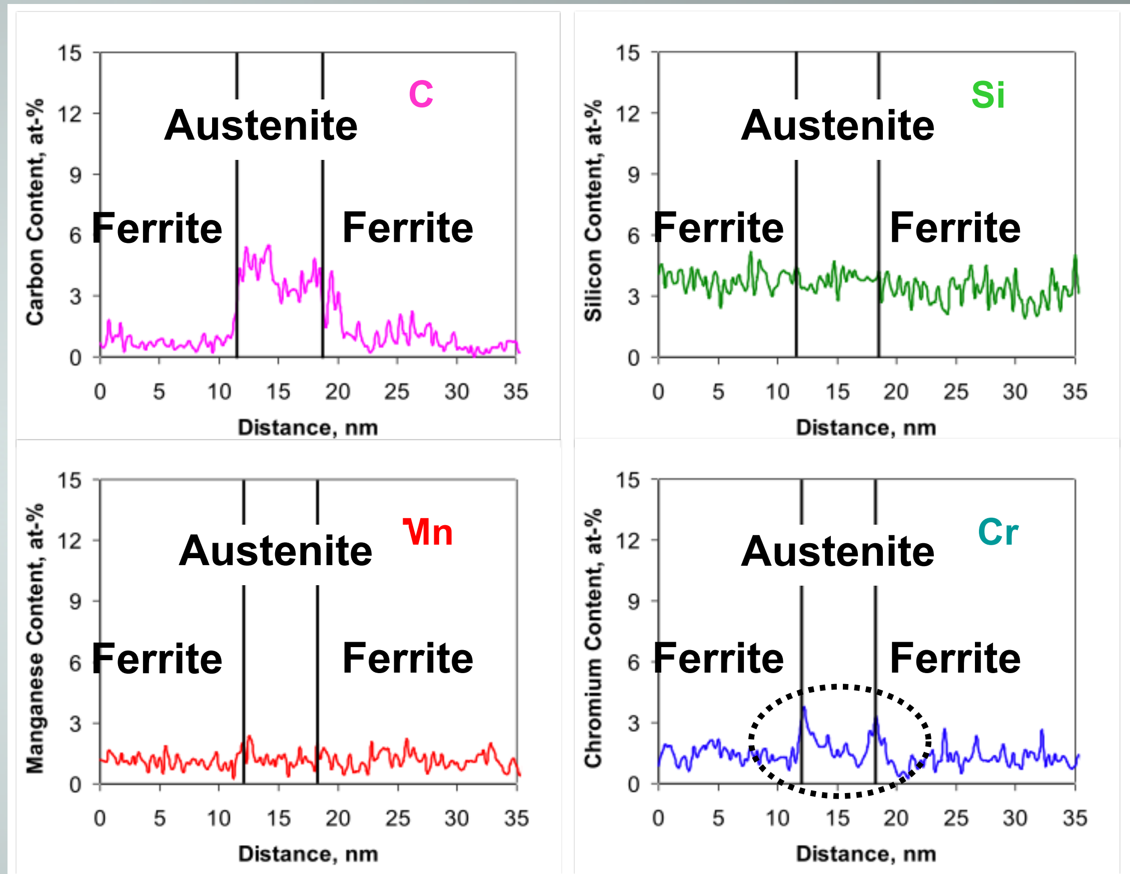
1h at 400ºC is not enough

Distribution through the interface γ/α

450ºC for 30 min



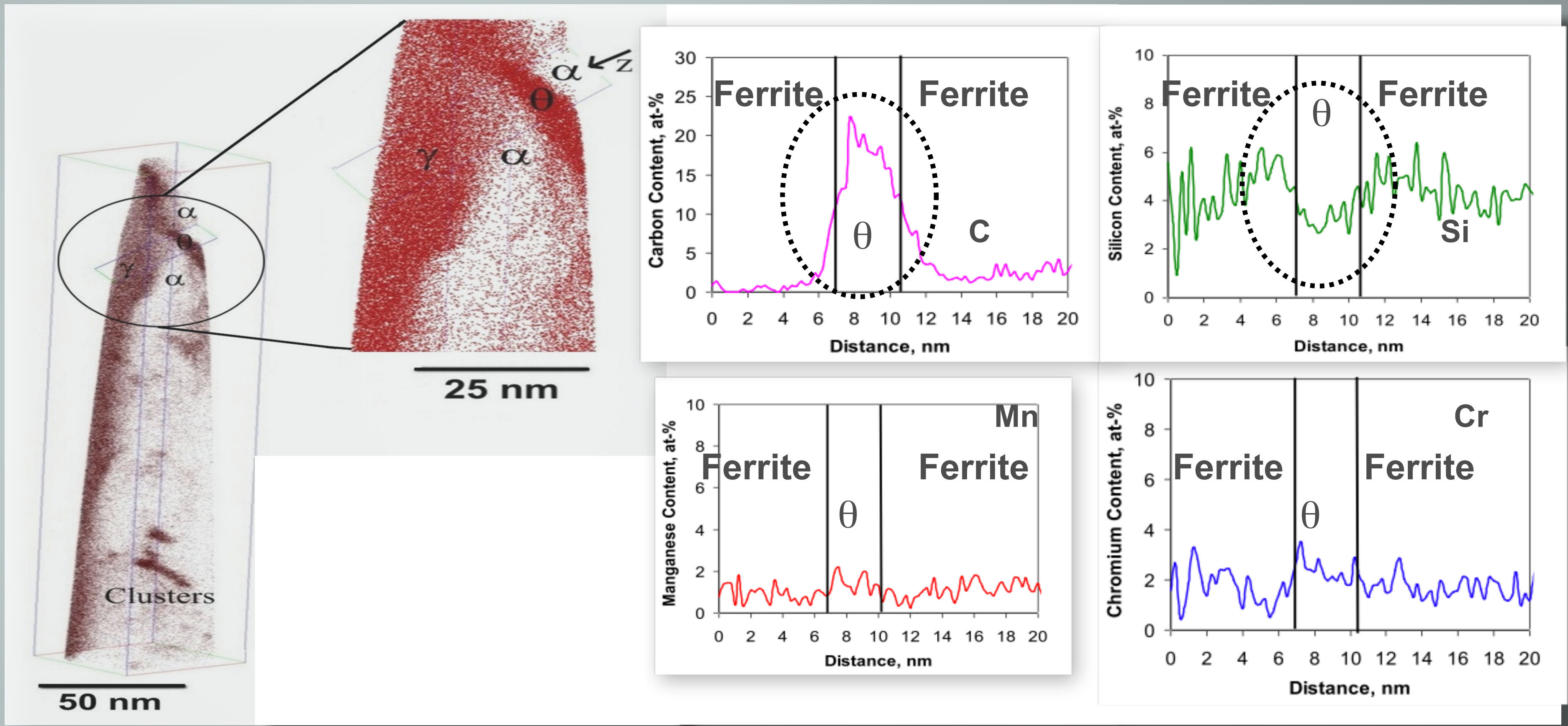
3.5 at. %



Only Cr partition across the interface. Elemental Spike indicates Negligible Partitioning Local Equilibrium (NPLE).

Asutenite decomposes before equilibrium is reached at the interface.

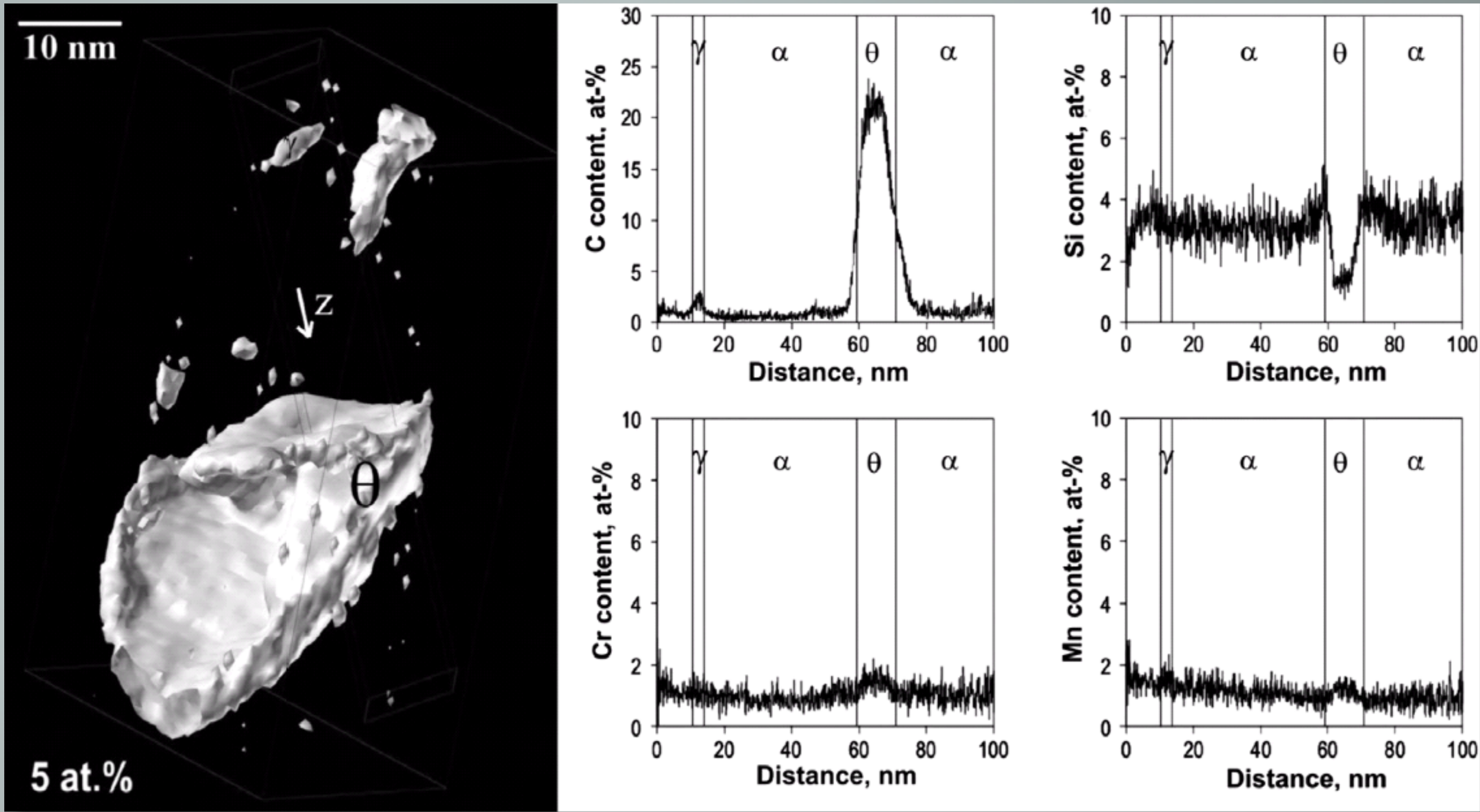
Distribution through the interface θ/α



400ºC for 30 min

Early stages of tempered cementite, C and Si redistribution

Distribution through the interface θ/α



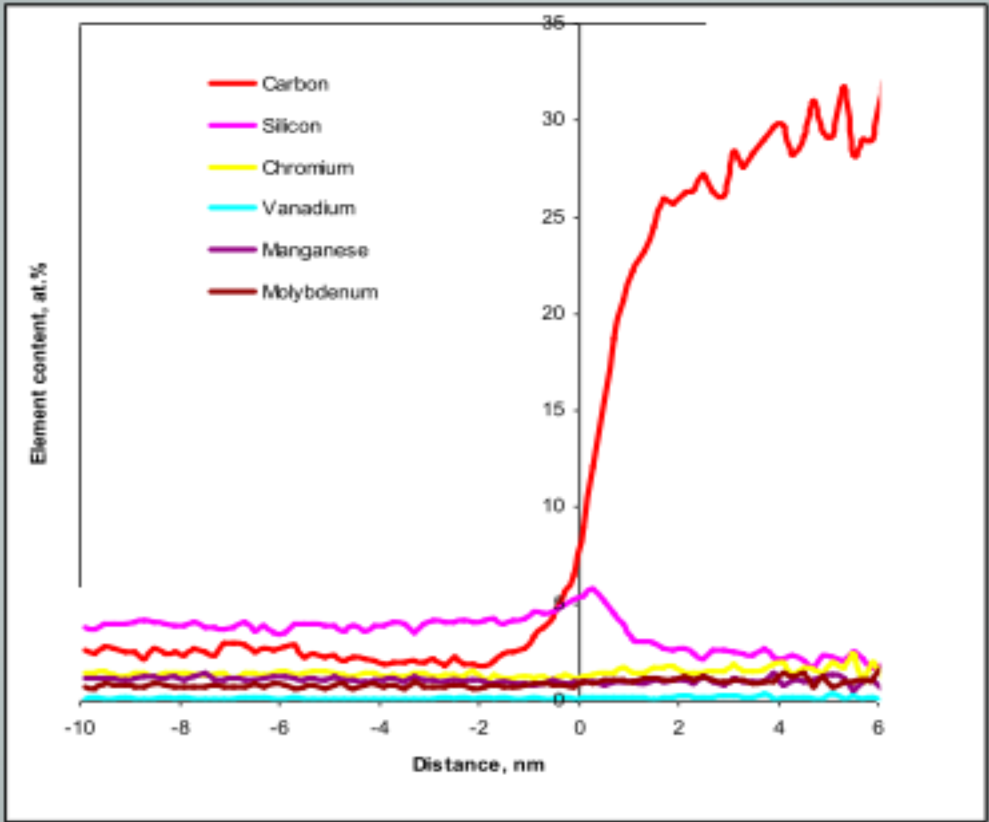
400ºC for 60 min

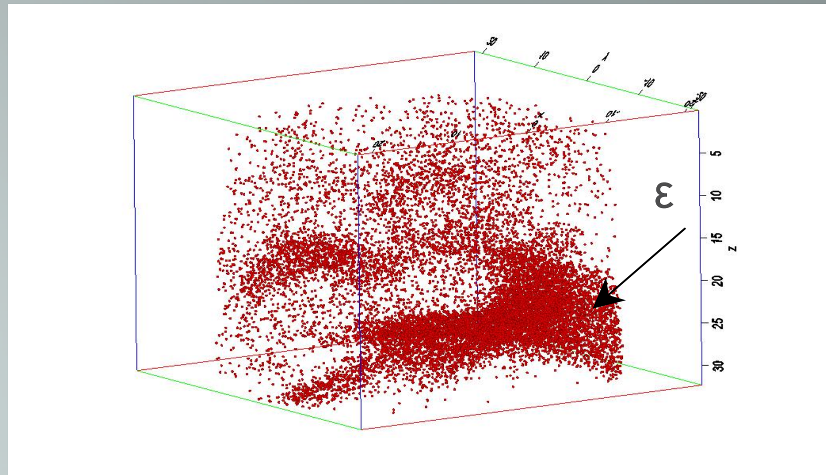
Higher extent of C, Si, Cr and Mn redistribution

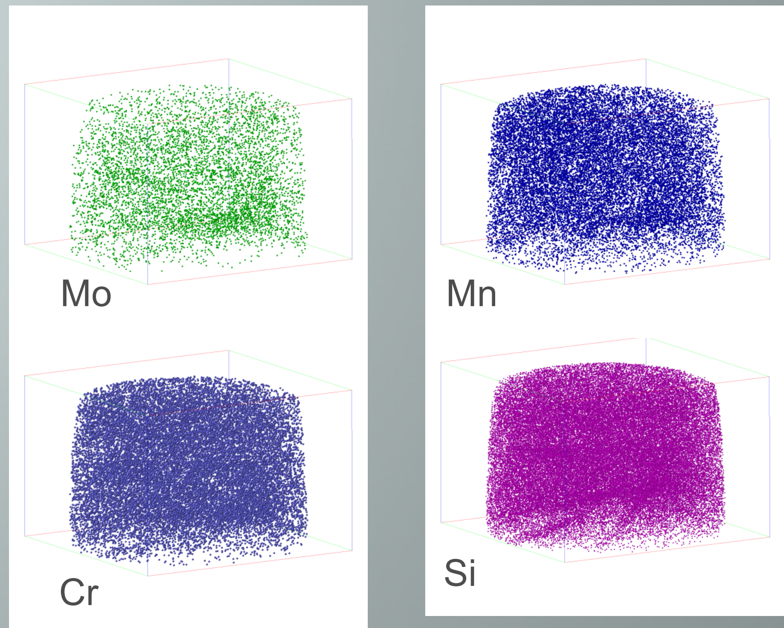
Carbide precipitation during tempering
Moving towards equilibrium as T and t increases

Carbide precipitation during tempering
ε carbide

400ºC-30 min.



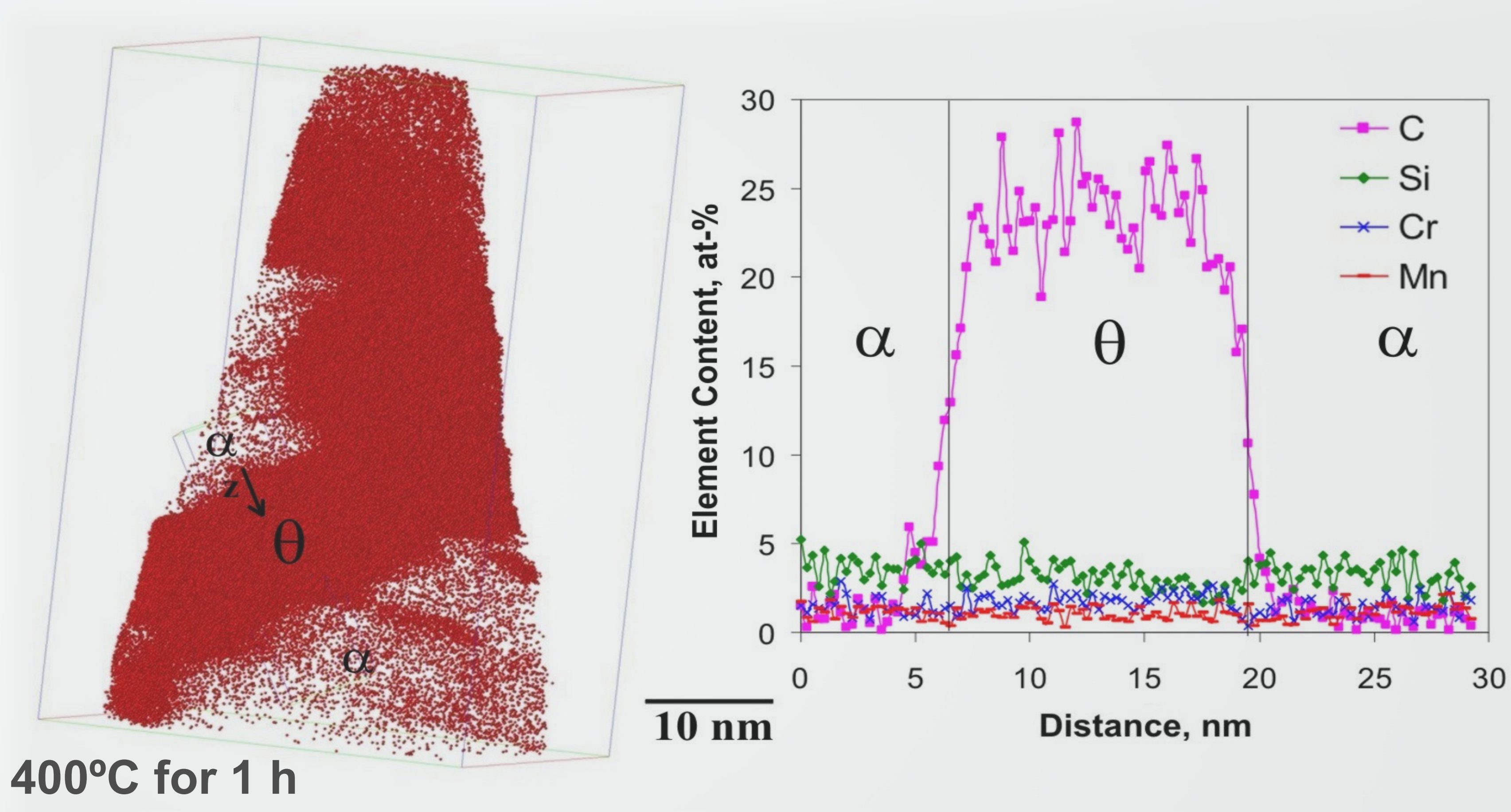




Fresh ε formed during tempering,
but already Si distribution happened

Epsilon (29.6+-1.3) Ferrite (2.6+-0.86)

Carbide precipitation during tempering

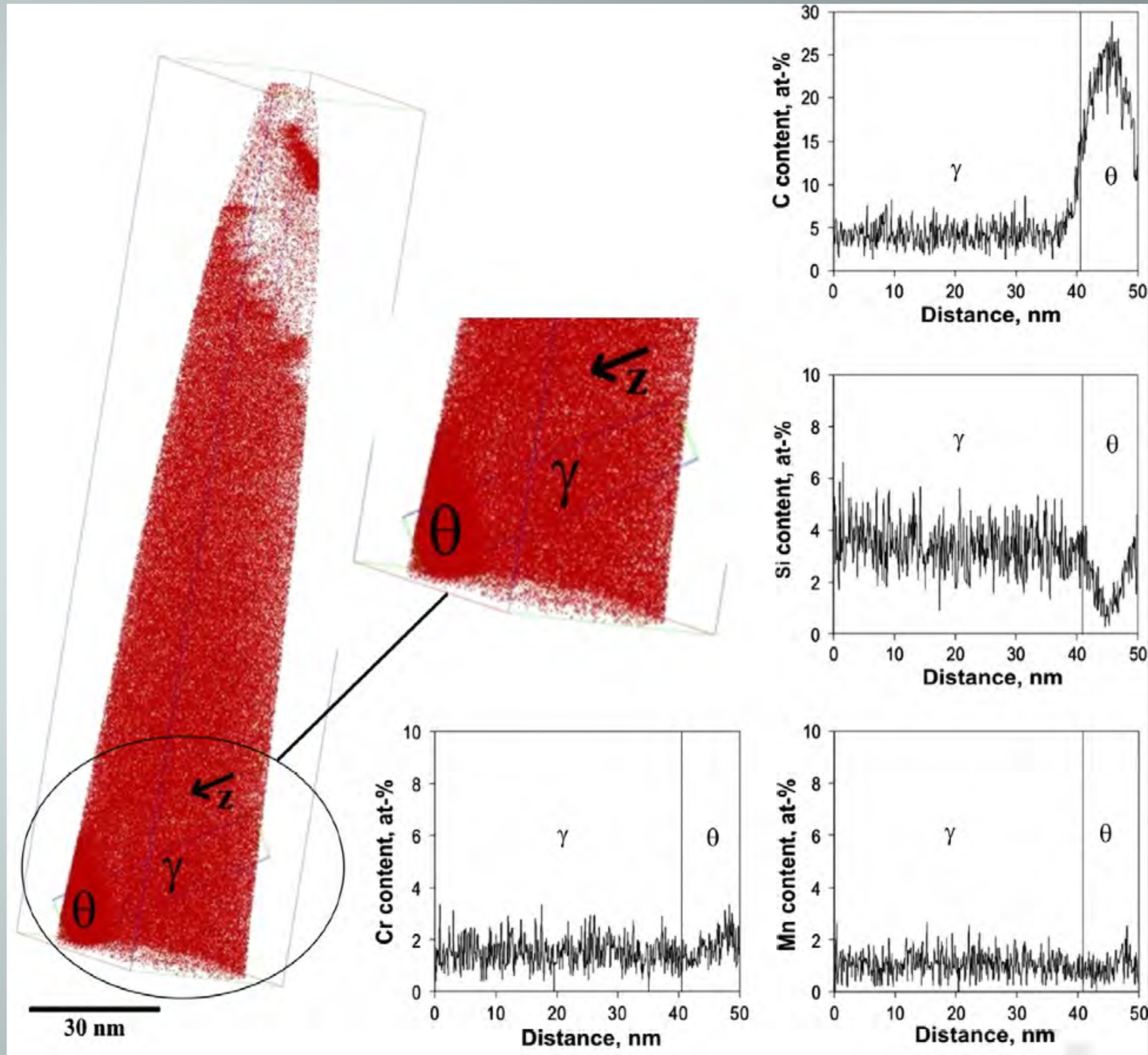


Fresh θ formed during tempering is also precipitated under paraequilibrium conditions
Neither elemental spikes nor segregation of Si Cr, or Mn were observed
at the cementite interface

Carbide precipitation during tempering

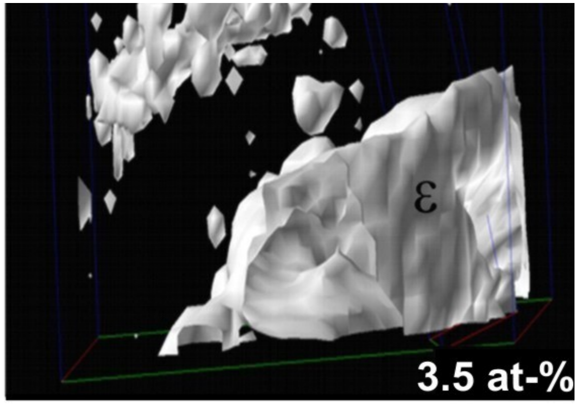
450ºC for 30 min

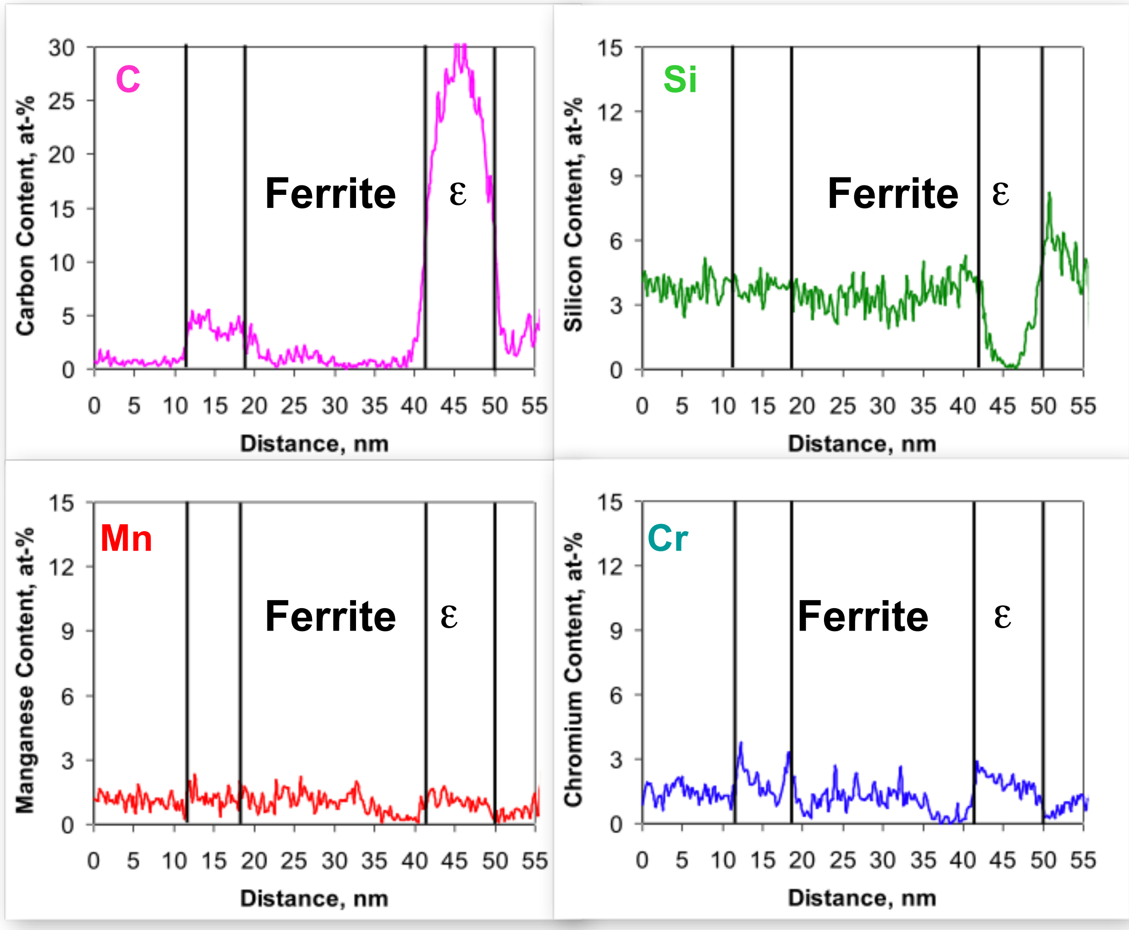
Initiation of the redistribution of silicon,
But there is no evidence for gross redistribution of Cr and Mn after tempering at 450 C for 30 min



ε Carbide precipitation

450ºC for 30 min

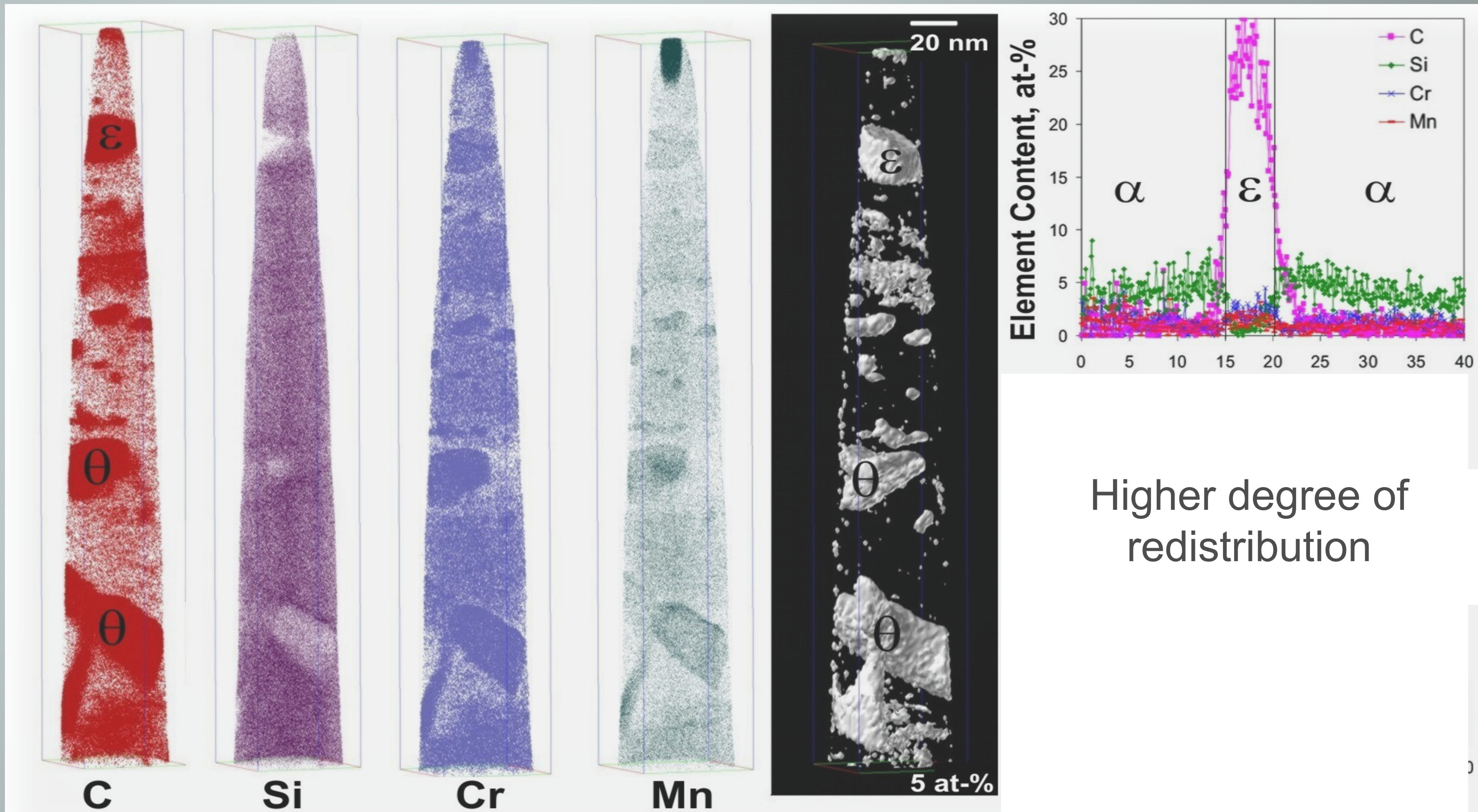




Significant depletion of Si detected
Slight enrichment of Cr and Mn

ε Carbide precipitation

500ºC for 30 min

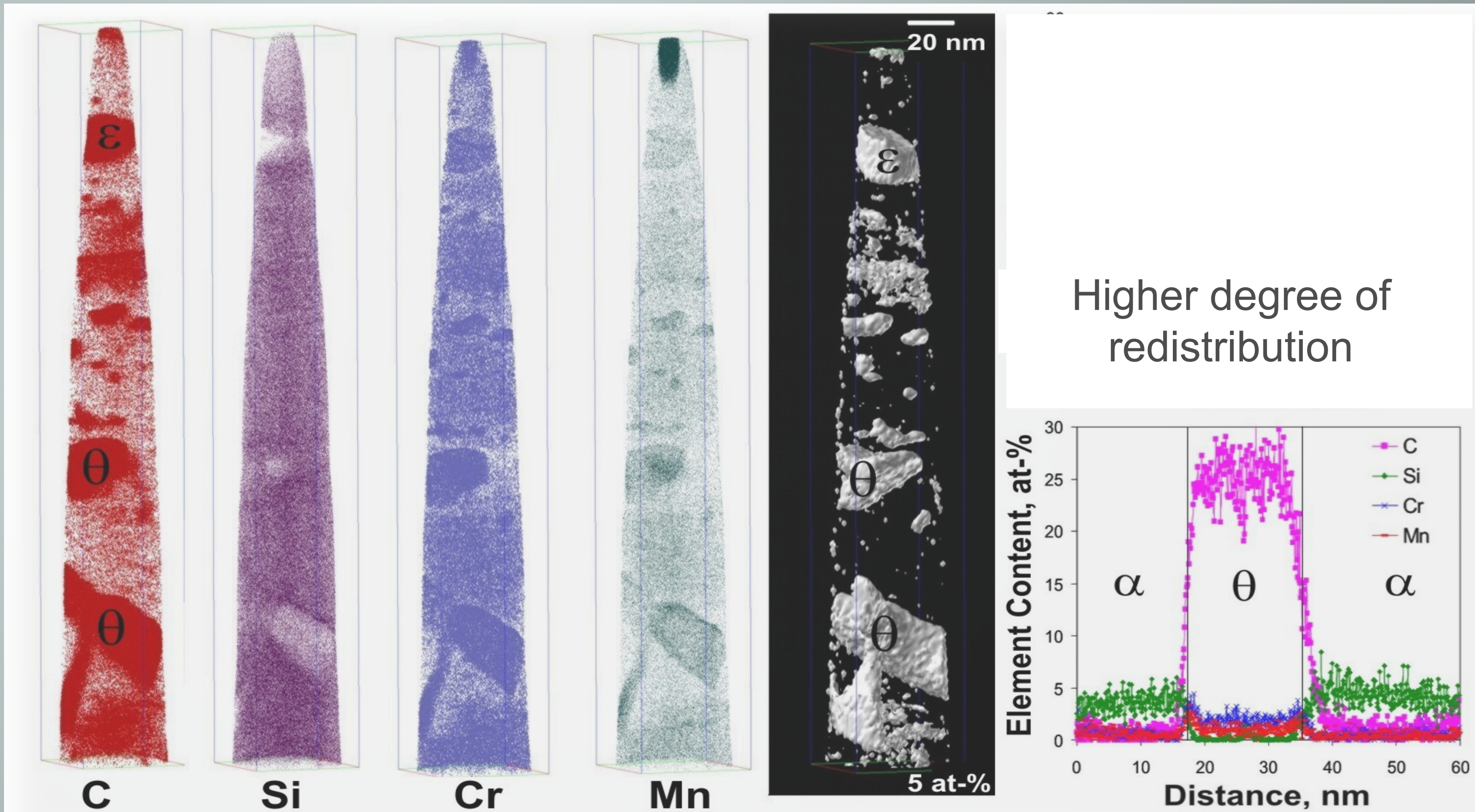


Higher degree of redistribution

Further tempering enhances redistribution of Cr and Mn

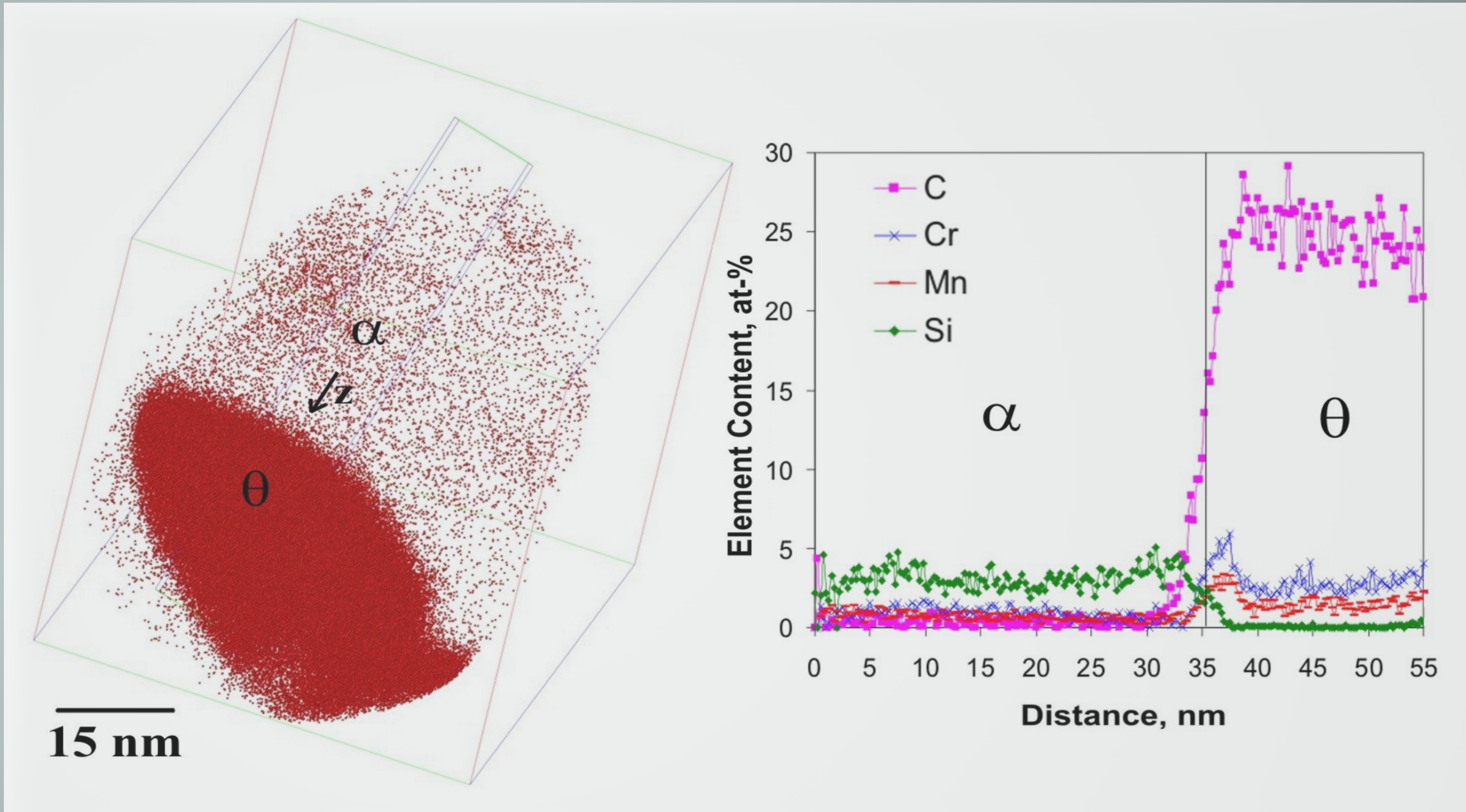
θ Carbide precipitation

500ºC for 30 min



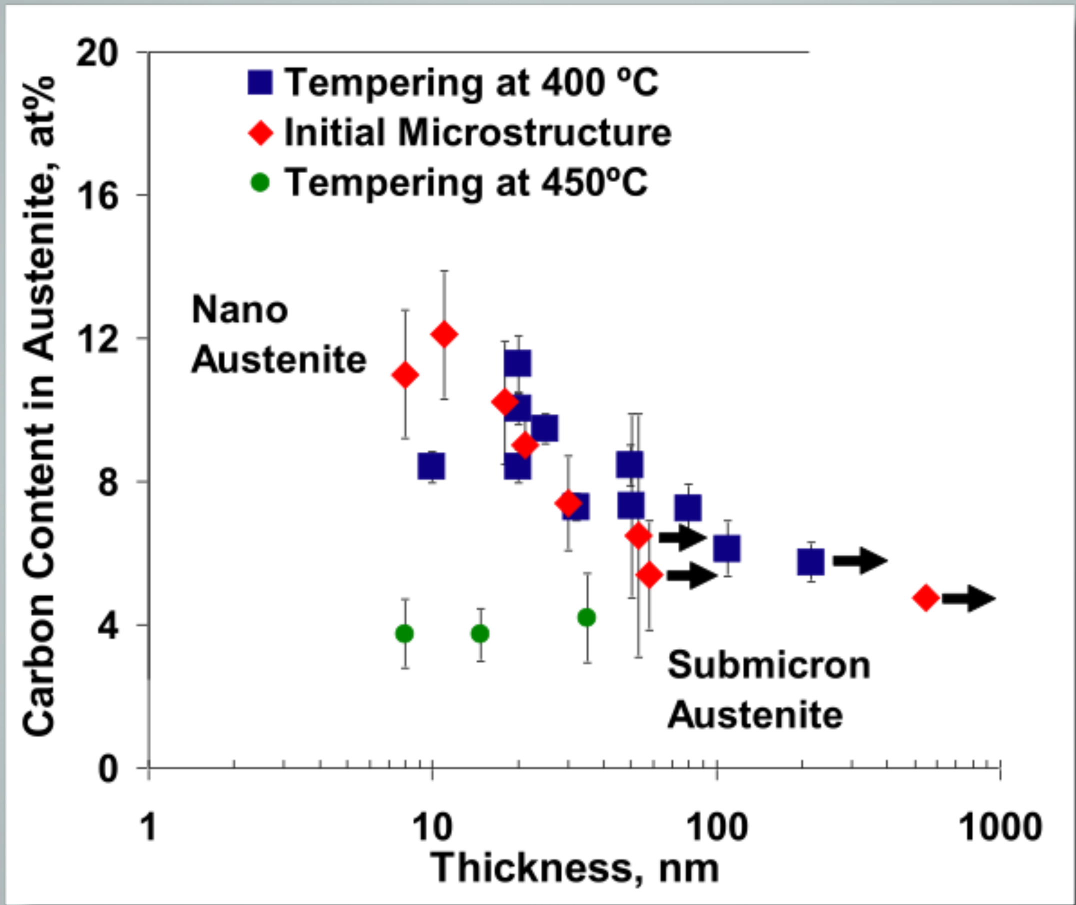
Somewhere between paequilibrium and equilibrium

550ºC for 1 h



Very close to equilibrium, still some Cr and Mn spikes are evident, more T and t for partitioning local equilibrium (PLE) condition

Carbon content in austenite after tempering

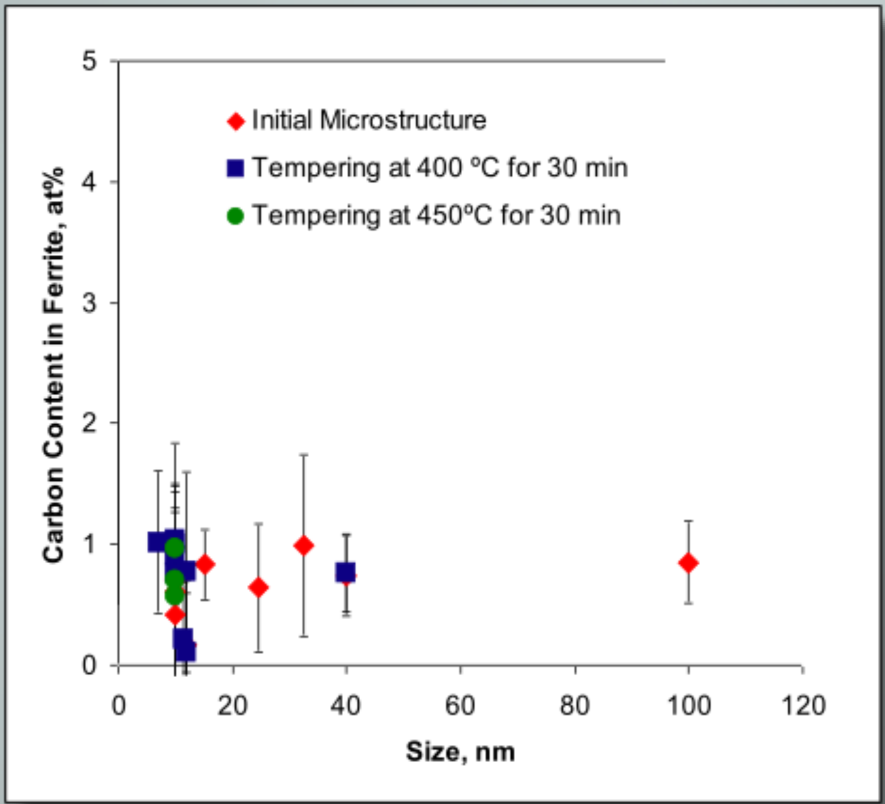


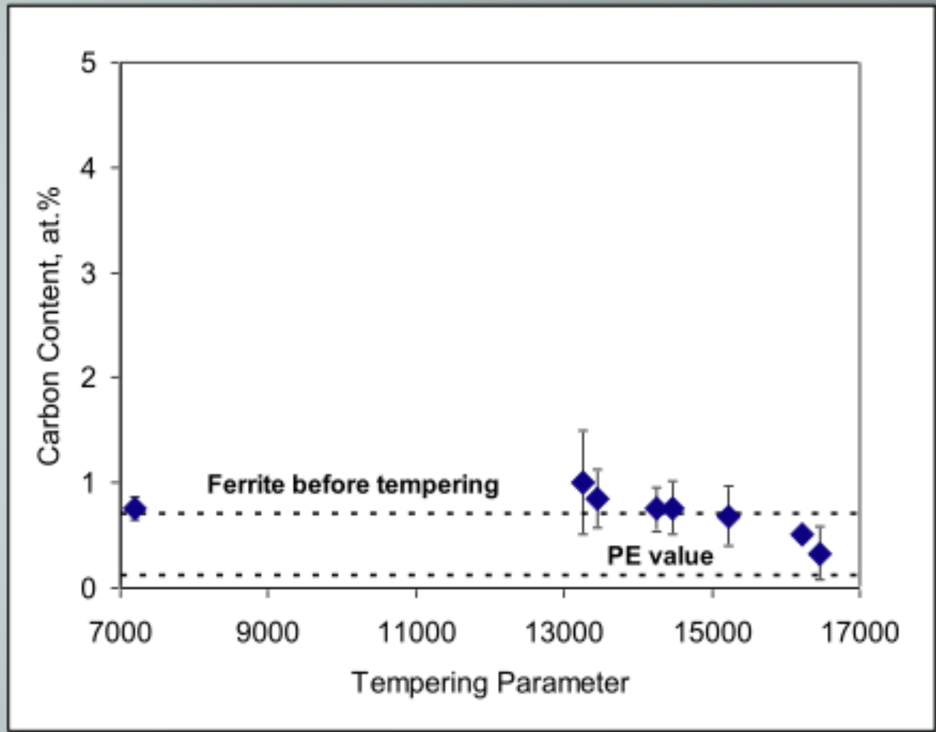
Remember that C distribution in γ is not homogeneous, i.e the smaller the richer in C.

Tempering at 400ºC does not change the situation.

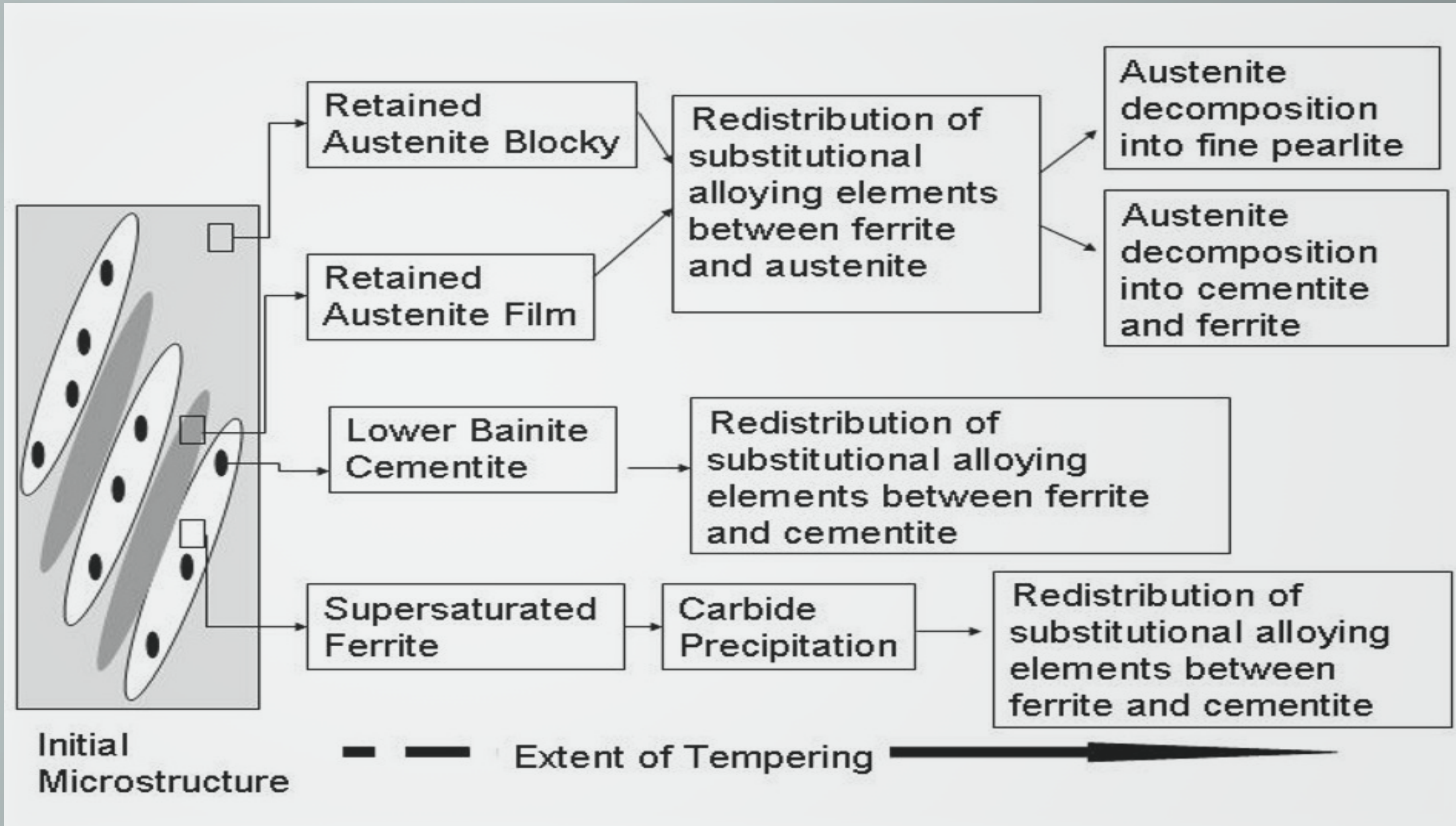
Tempering at 450ºC exhibits a drop in C due to precipitation

Carbon content in ferrite after tempering





Summary



Retained Austenite Blocky
Retained Austenite Film
Lower Bainite Cementite
Supersaturated Ferrite
Carbide Precipitation
Redistribution of substitutional alloying elements between ferrite and austenite
Austenite decomposition into fine pearlite
Austenite decomposition into cementite and ferrite
Redistribution of substitutional alloying elements between ferrite and cementite
Redistribution of substitutional alloying elements between ferrite and cementite
Initial Microstructure
Extent of Tempering

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C. Capdevila (CENIM-CSIC)
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More information at
MATERALIA Group web page

Google for MATERALIA + CENIM

Many thanks for your attention !!

Carbide precipitation during tempering
Moving towards equilibrium as T and t increases.