Towards the limits of strength:

Design and understanding of ultra high strength steels

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Colloquium 19, Nov. 2010 LMU

Overview

- Motivation for high strength steels
- TRIP, TWIP
- Maraging TRIP
- Quench-partition stainless steel
- Pearlite: strongest bulk material
- High strength electrical steel
- Conclusions and challenges

Raabe: Adv. Mater. 14 (2002), Roters et al. Acta Mater.58 (2010)

New materials for key technologies: Aero-space

- Titanium
- Aluminium
- Magnesium
- Nickel
- Steels
- Intermetallics

New materials for key technologies: mobility on land and water

Steels
Magnesium
Aluminium
Titanium

New materials for key technologies: Power plants

Steels
Nickel
Intermetallics

New materials for key technologies: Green energy

Steels

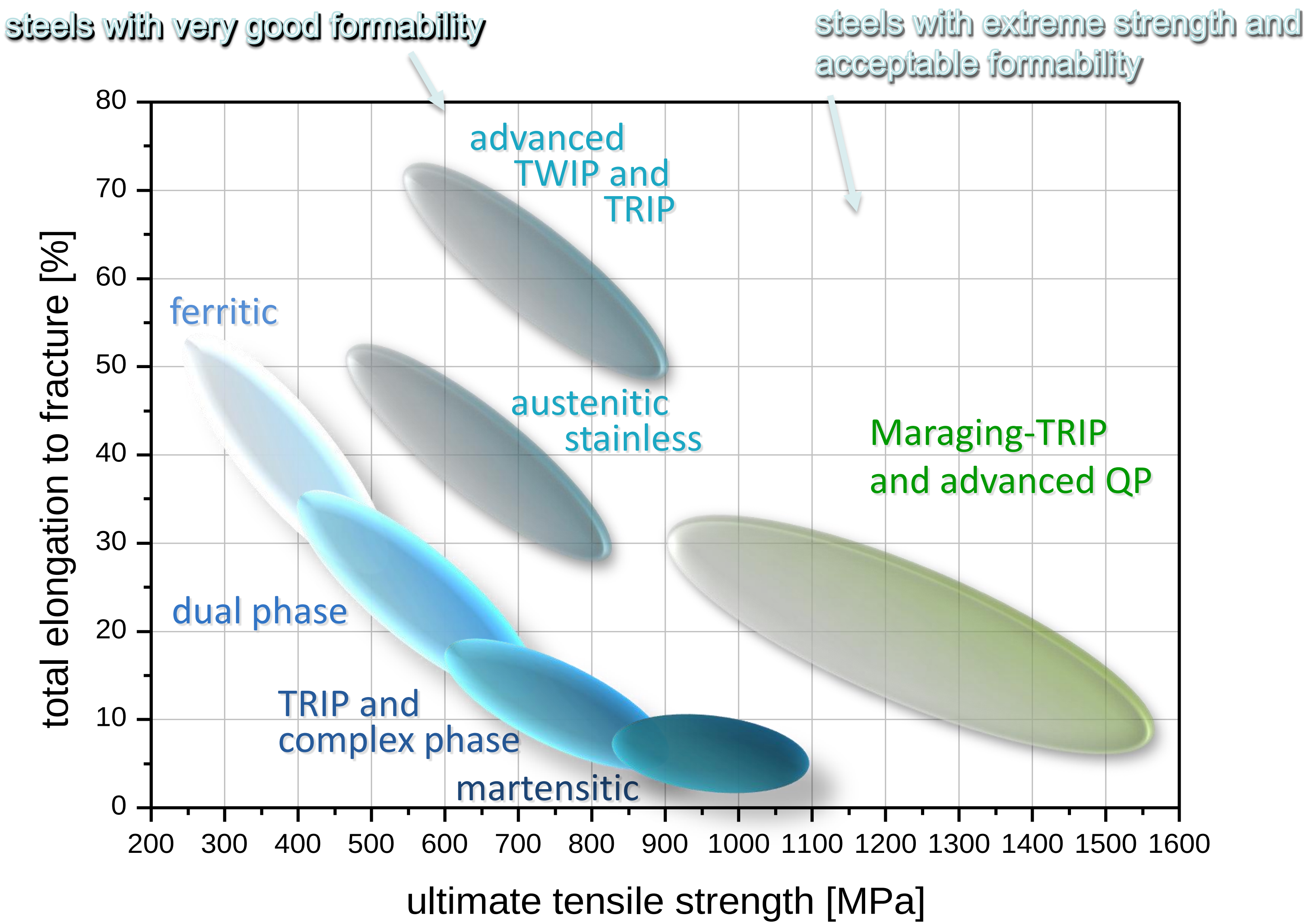
Cu(In,Ga)Se_2

CdTe

New materials for key technologies: infrastructure

Steels

Property profiles of steels



Raabe, Ponge, Dmitrieva, Sander: Scripta Mater. 60 (2009) 1141

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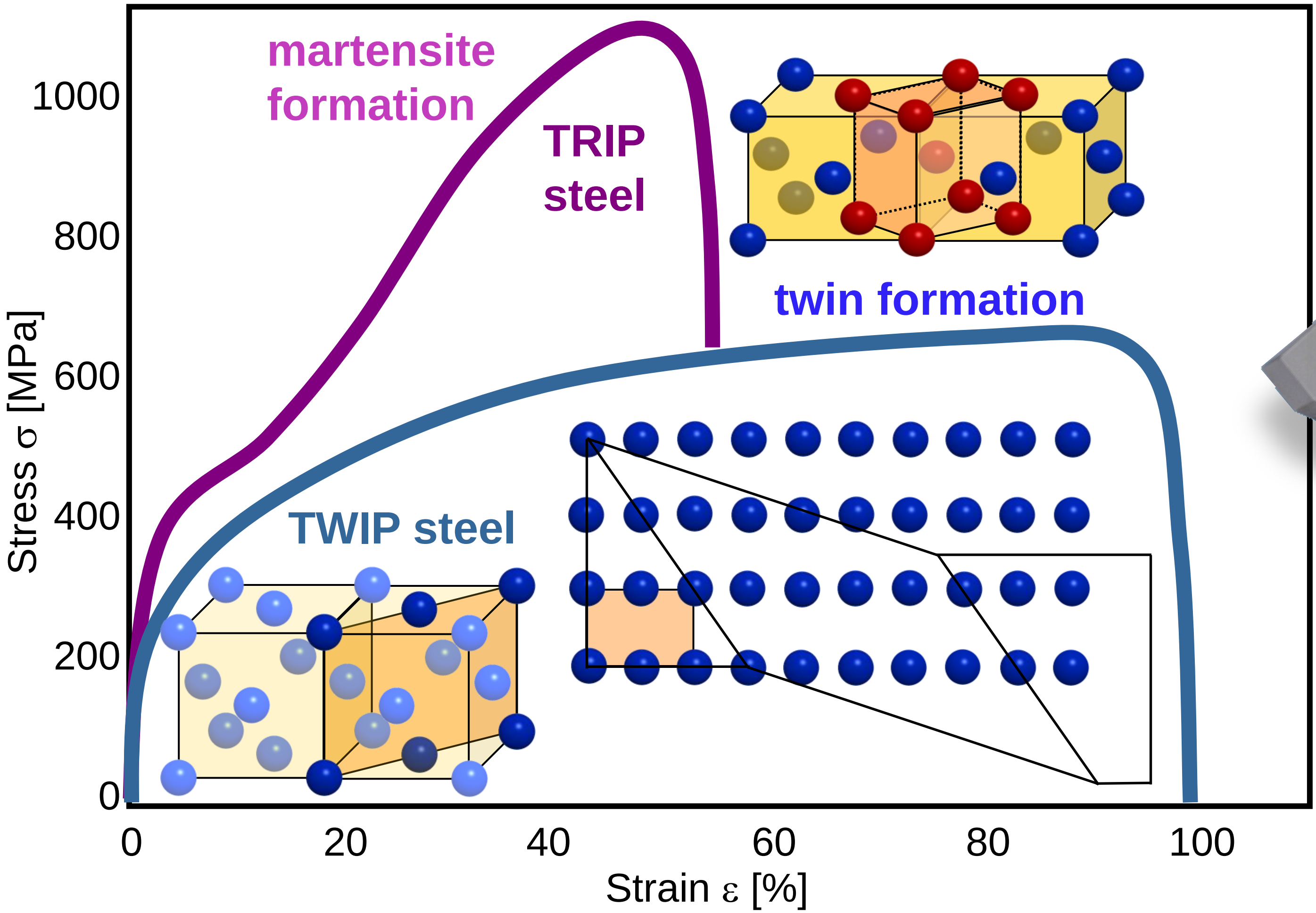
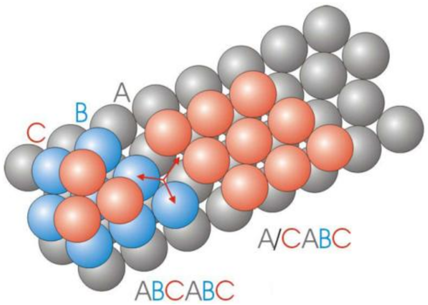
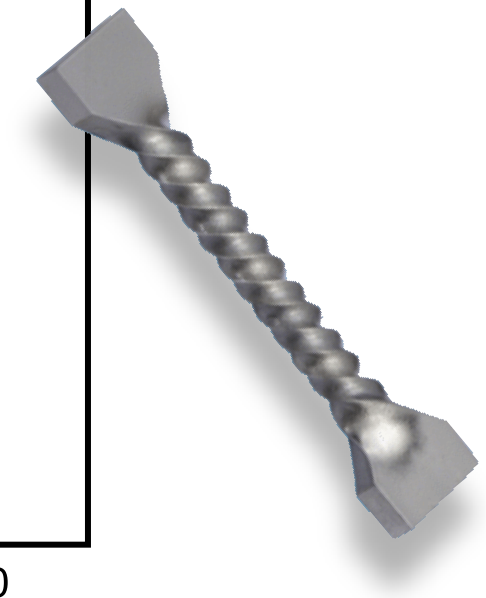
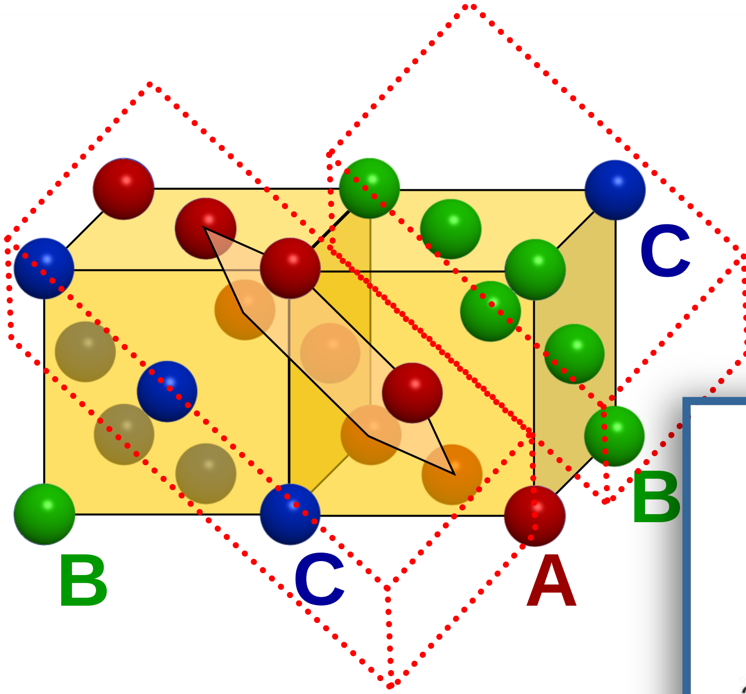
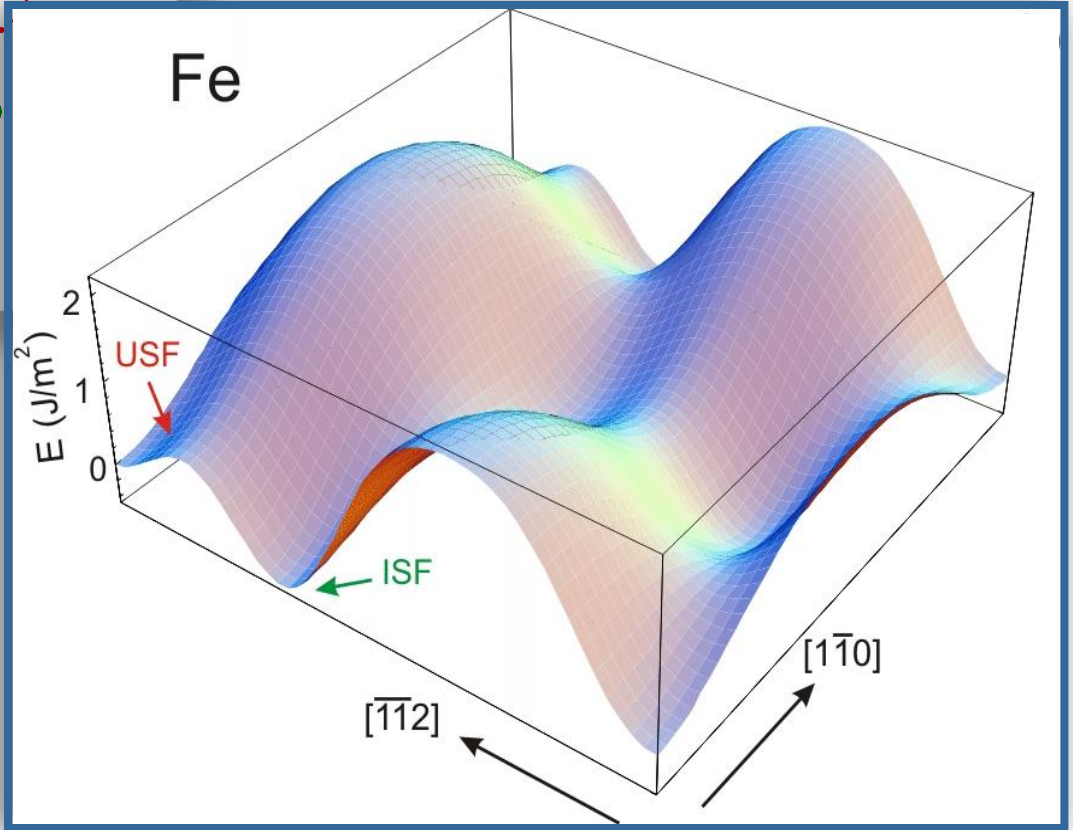

martensite
formation
TRIP
steel
twin formation
TWIP steel
1000
800
600
400
200
0
Stress σ [MPa]
0
20
40
60
80
100
Strain ε [%]

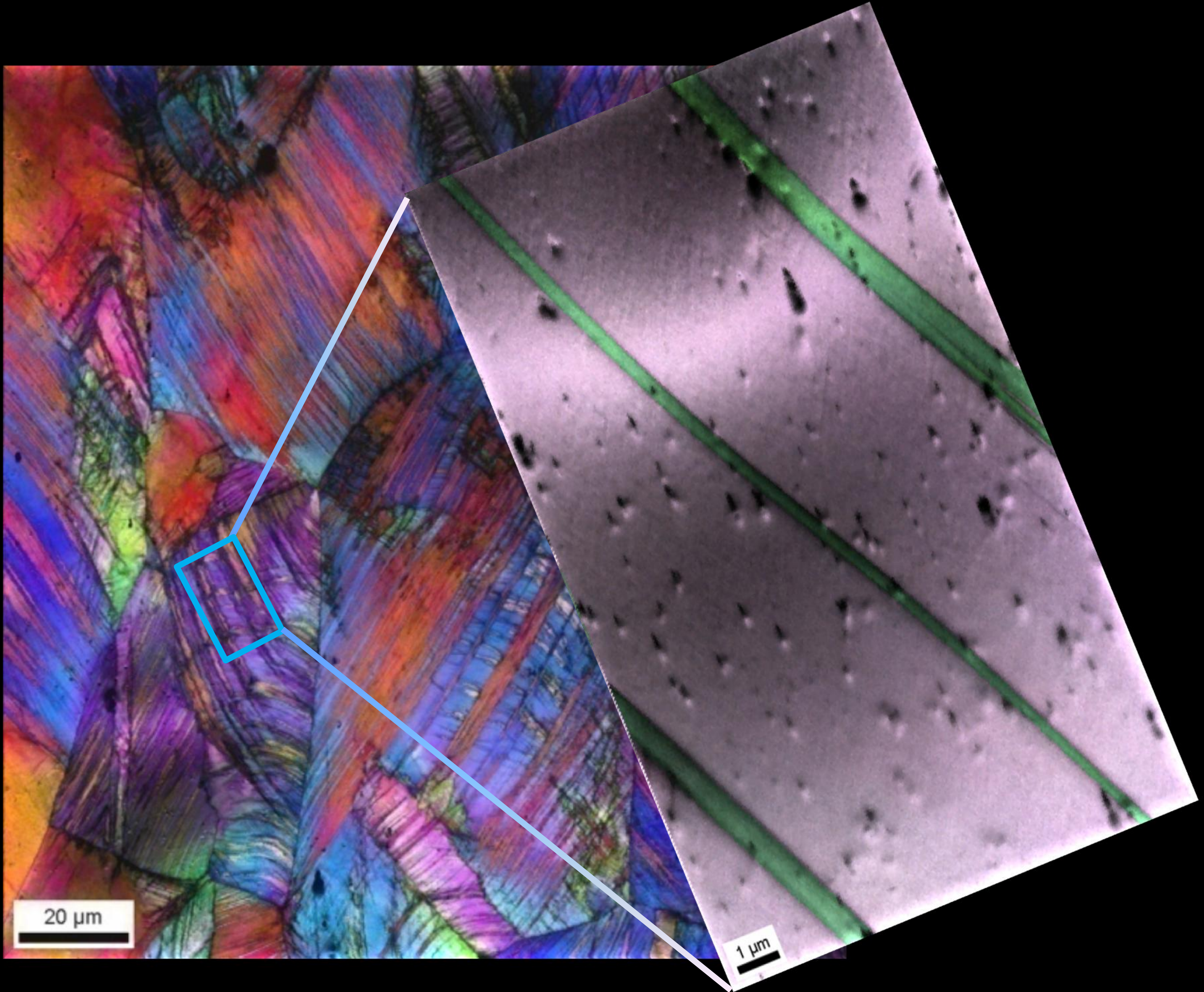

C
B
A
A/CABC
ABCABC

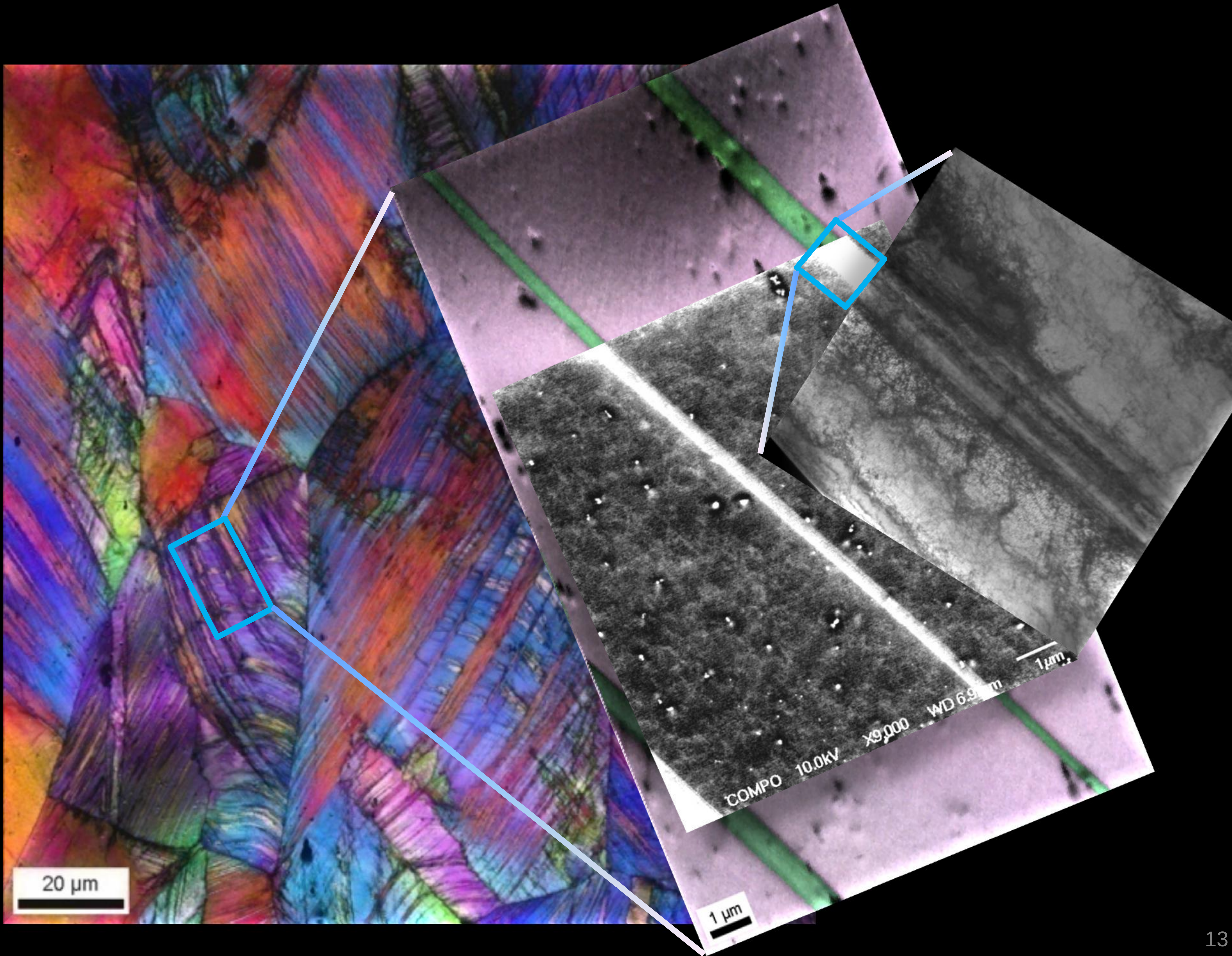


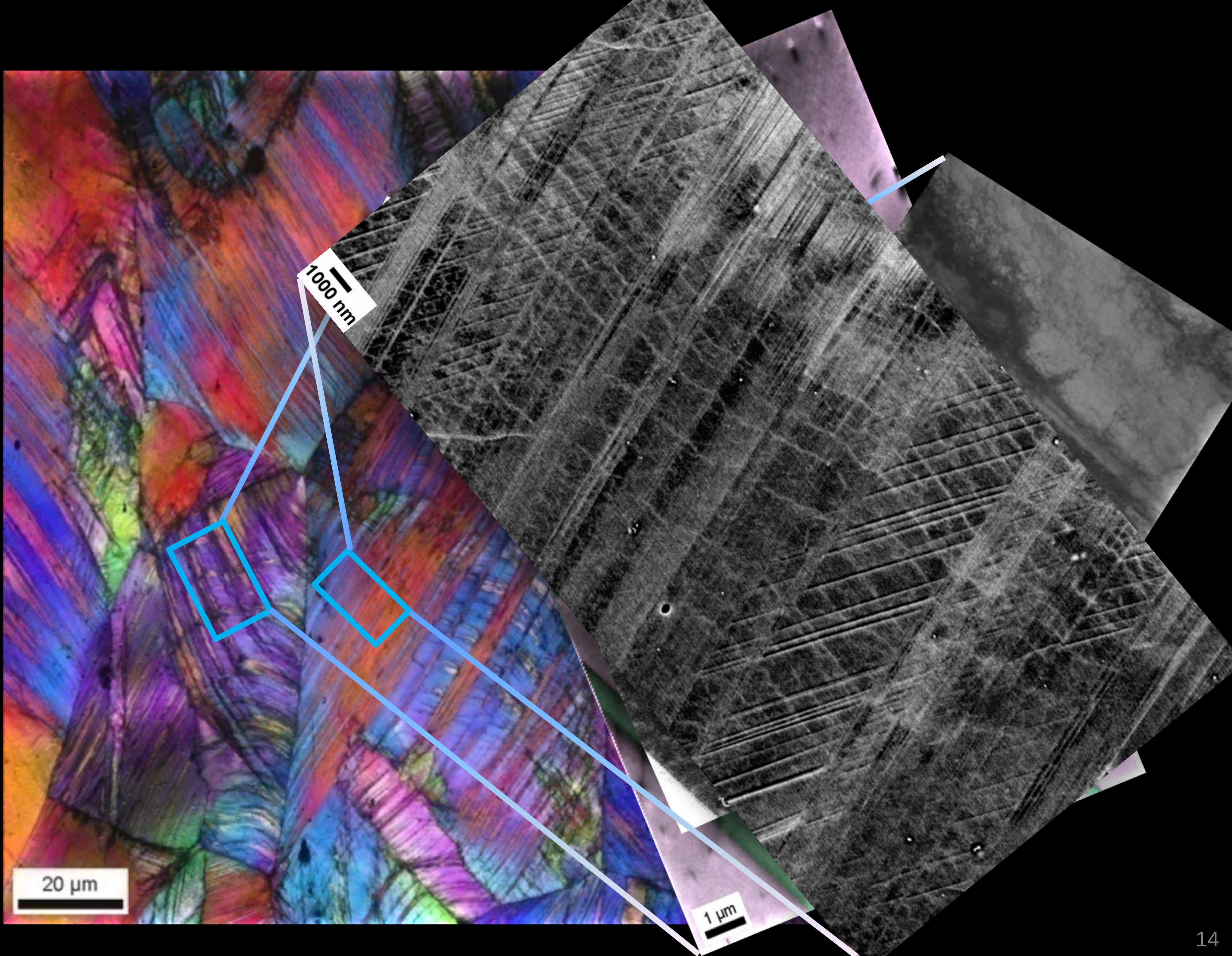

B
C
A
C
B


Fe
E (J/m^2)
0
1
2
USF
ISF
[$\bar{1}\bar{1}$2]
[1$\bar{1}$0]


20 µm


20 µm
1 µm


20 µm
1 µm
COMPO 10.0kV X9,000 WD 6.9 mm
1µm


20 µm
1000 nm
1 µm

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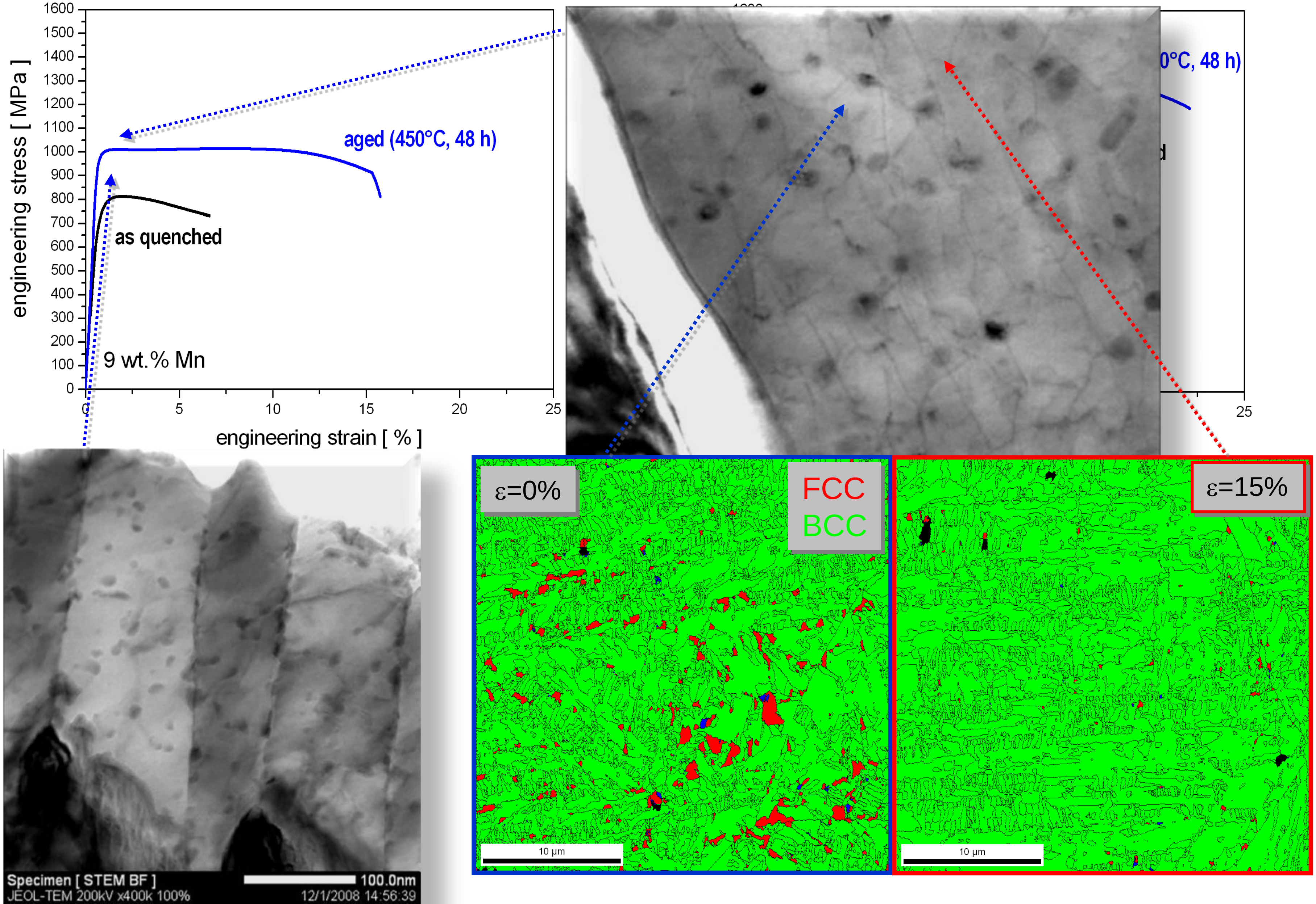
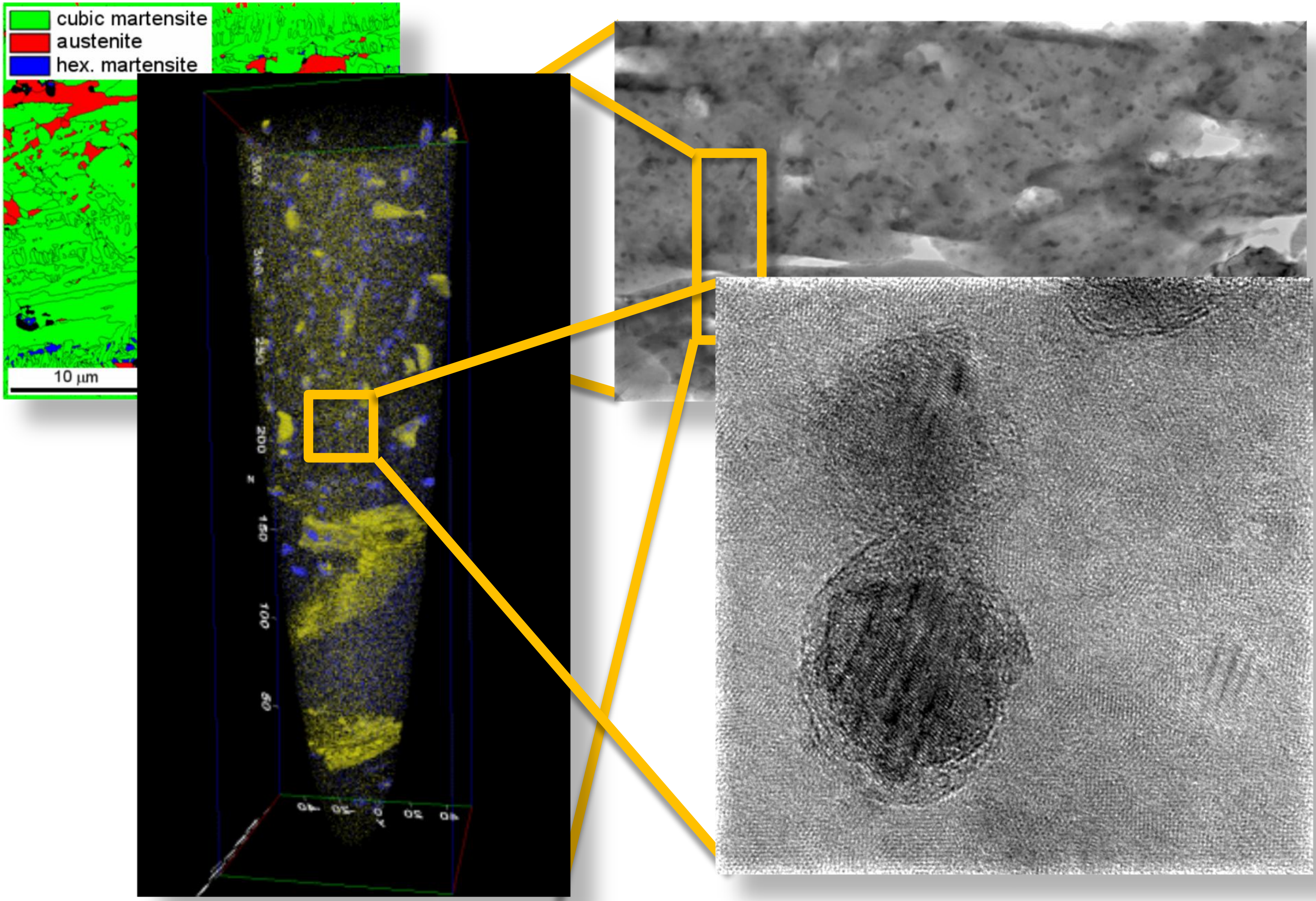
Tensile tests, maraging TRIP

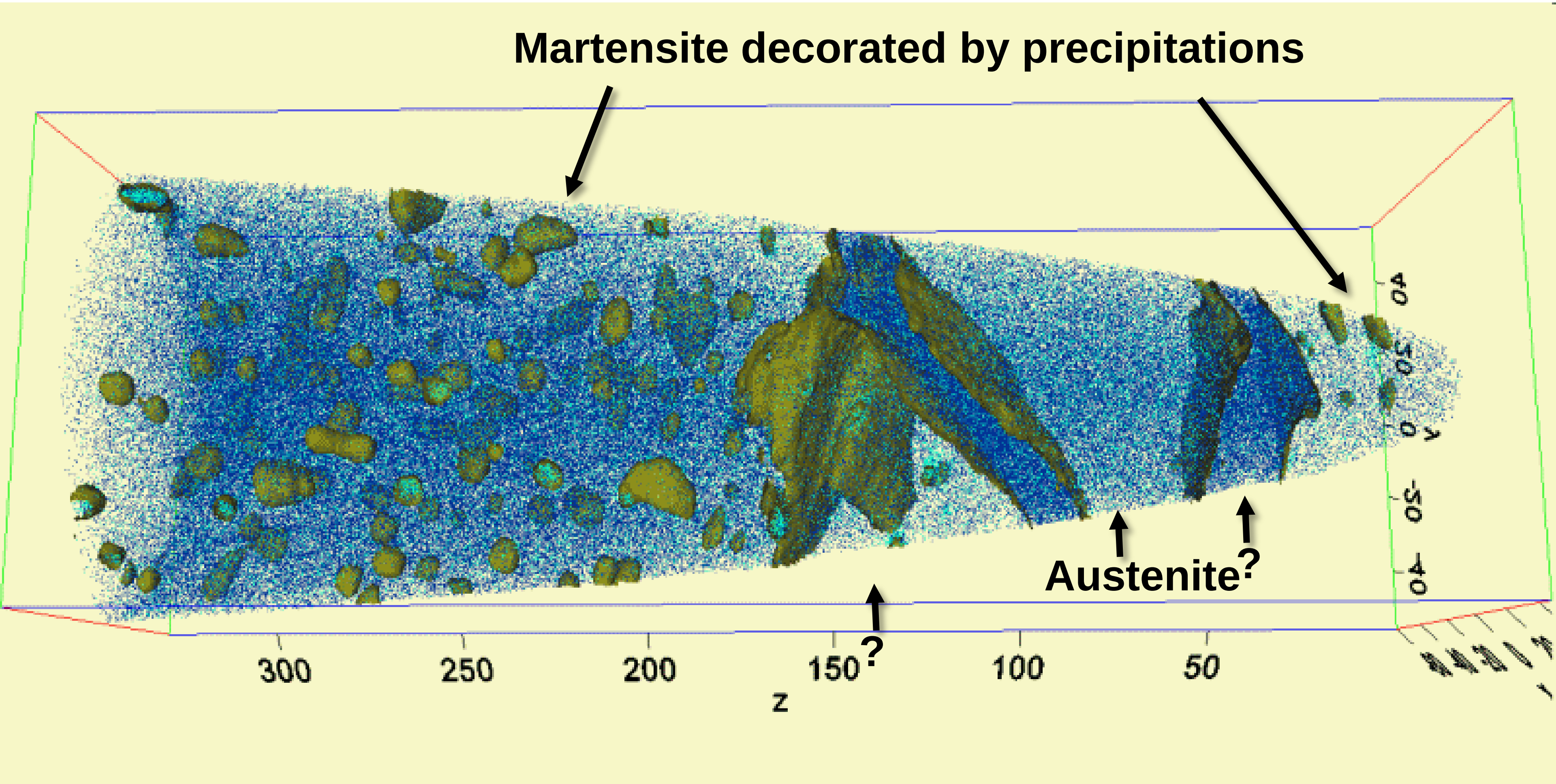


Microstructure hierarchy



Dmitrieva et al., Acta Mater, in press 2010

APT results: Atomic map (12MnPH aged 450°C/48h)



Mn atoms
Ni atoms
Mn iso-concentration surfaces at 18 at.%

70 million ions
Laser mode
(0.4nJ, 54K)

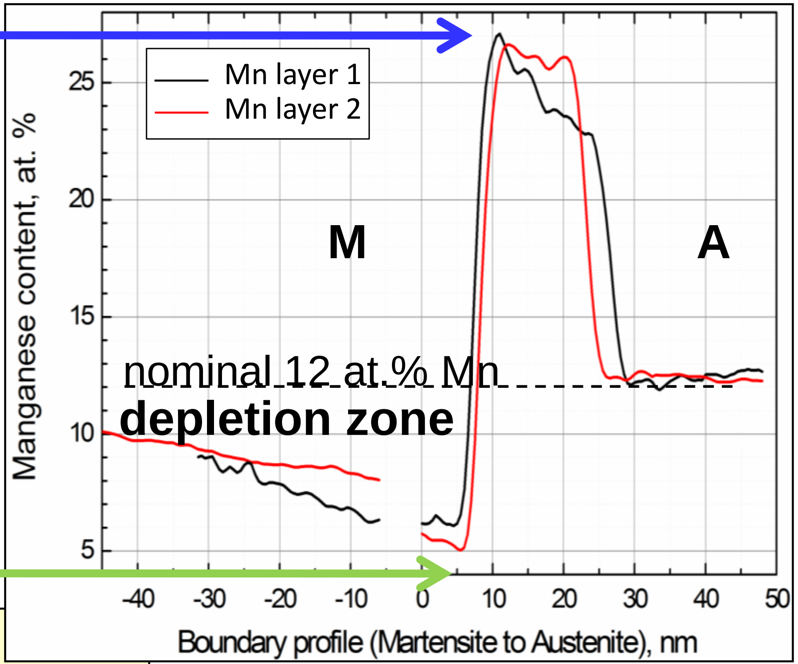
APT results: chemical profiles

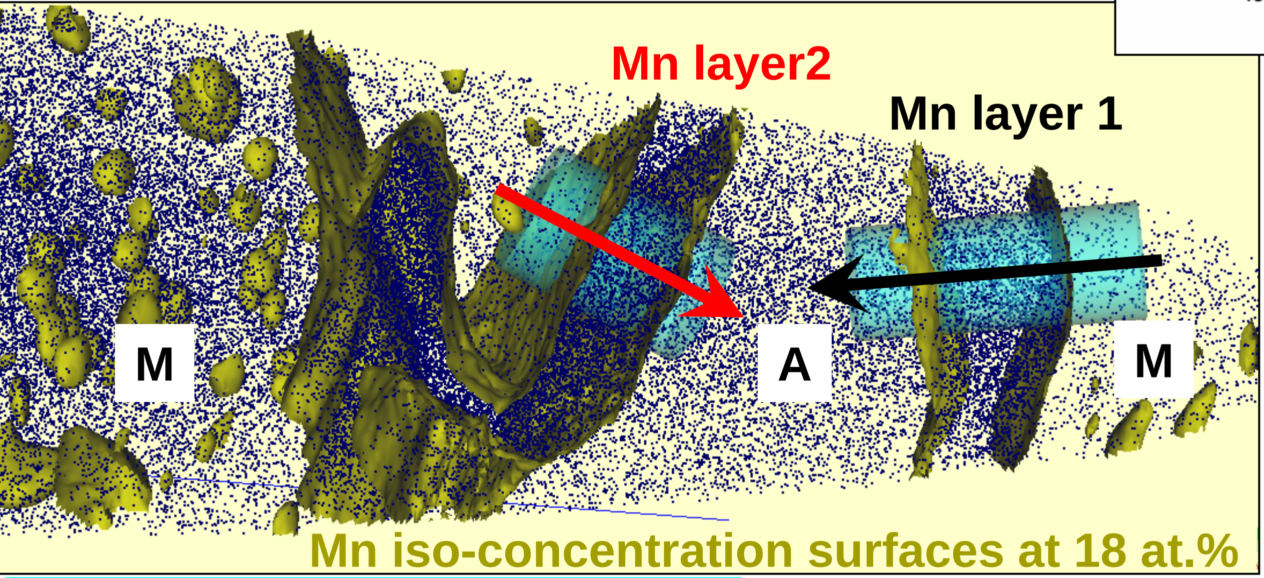
Thermo-Calc ⇒

Phase equilibrium Mn-contents:

27 at. % Mn in austenite (A)

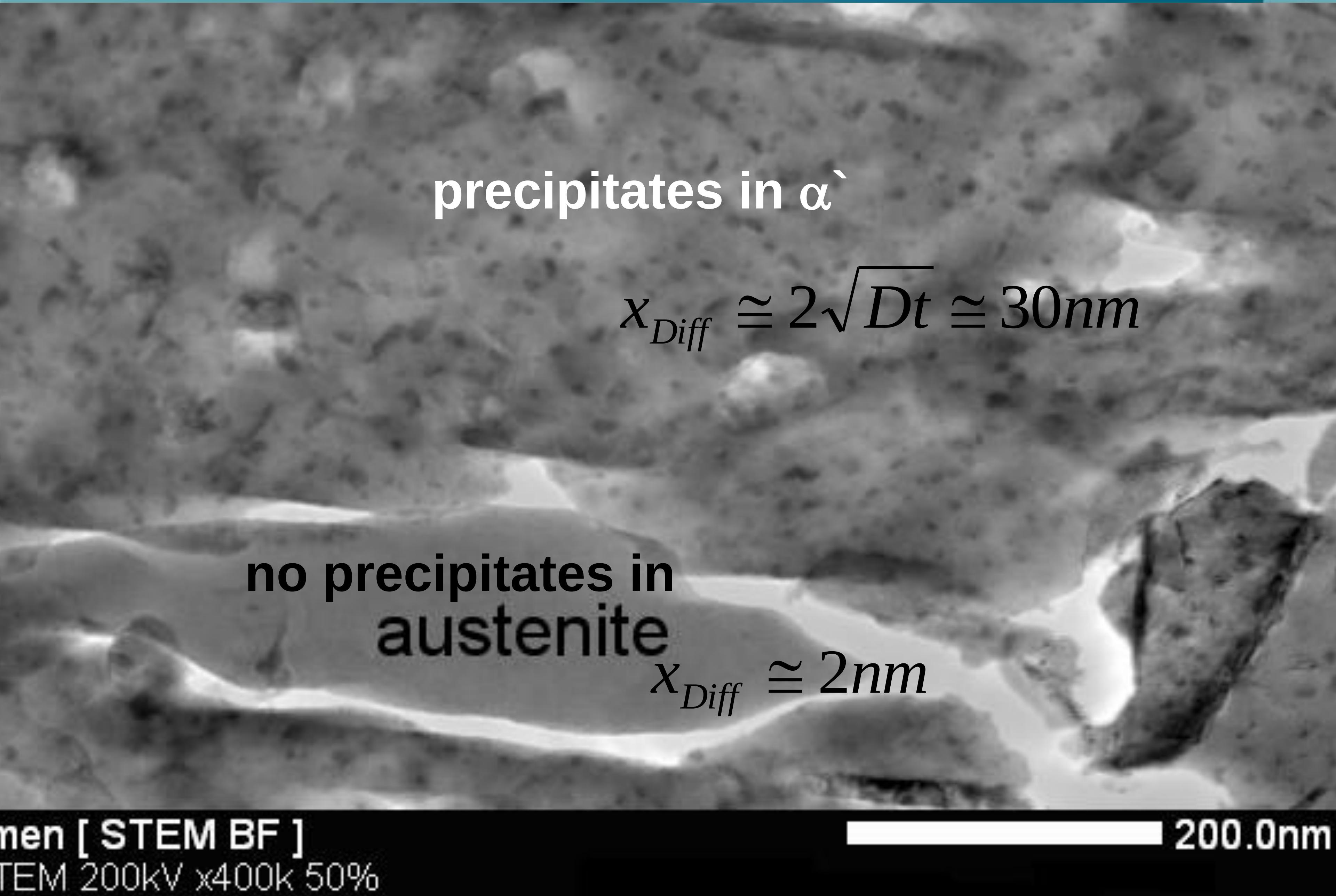
3 at. % Mn in ferrite (martensite) (M)





1D profile: step size 0.5 nm

12MnPH after aging (48h 450°C)



precipitates in α`

$$x_{Diff} \cong 2\sqrt{Dt} \cong 30nm$$

no precipitates in austenite

$$x_{Diff} \cong 2nm$$

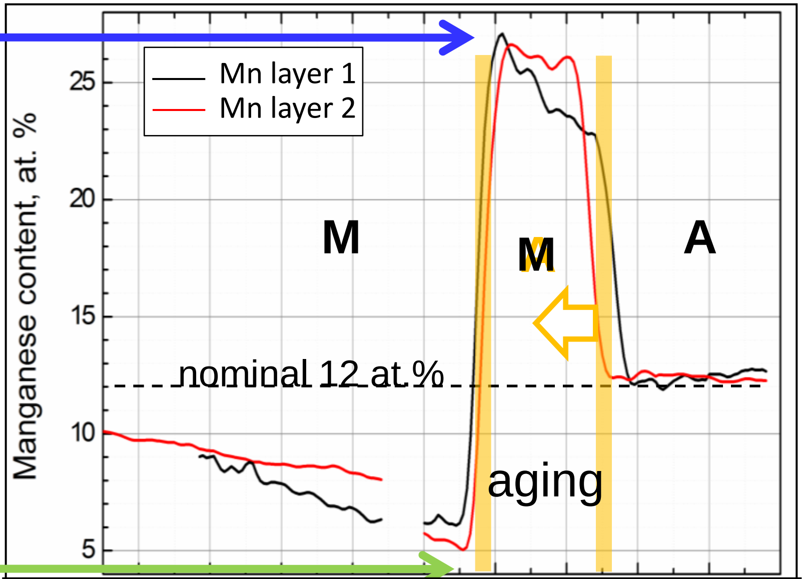
APT results and simulation: DICTRA/ThermoCalc

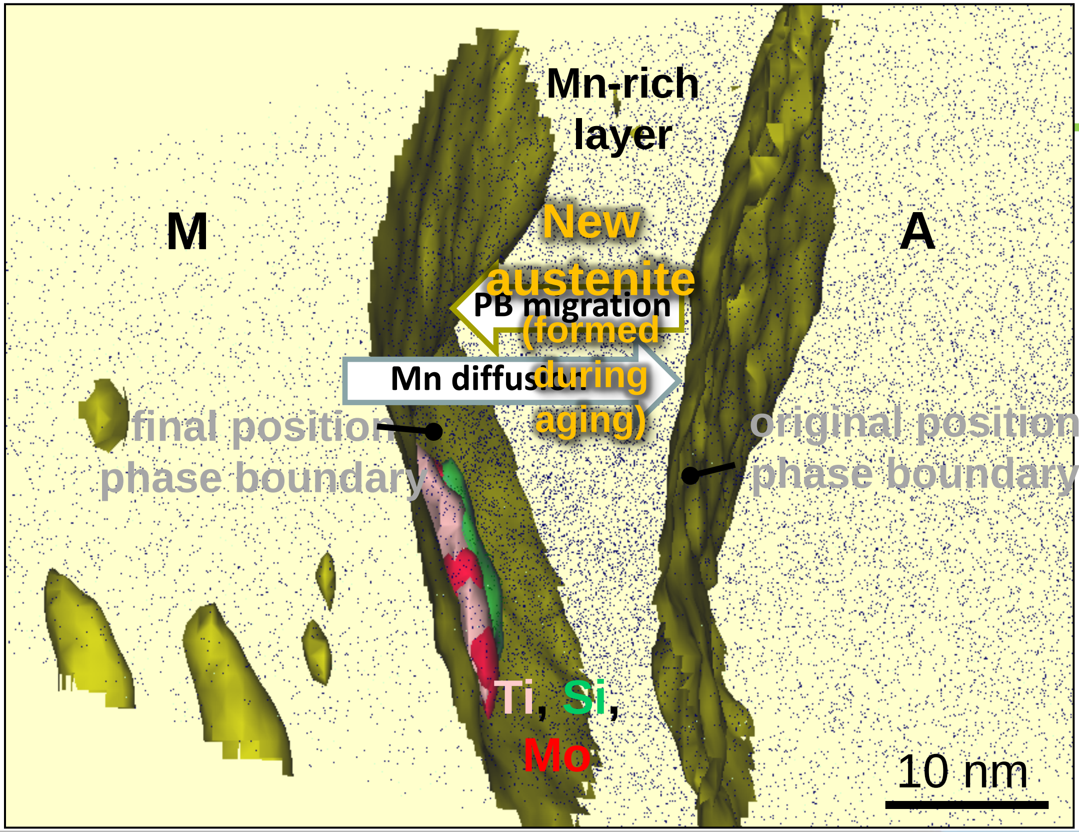
Thermo-Calc ⇒

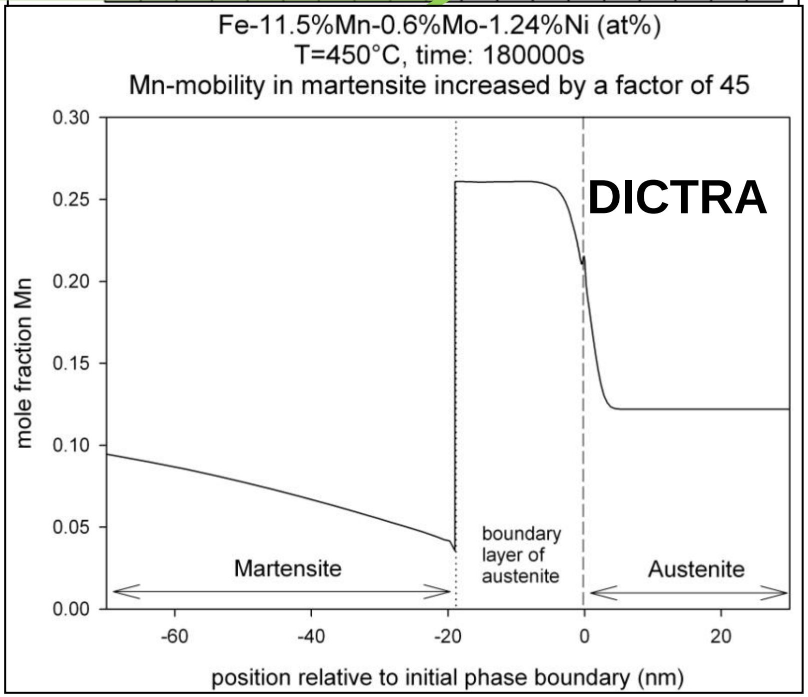
Phase equilibrium Mn content:

27 at. % in austenite

3 at. % in ferrite (martensite)







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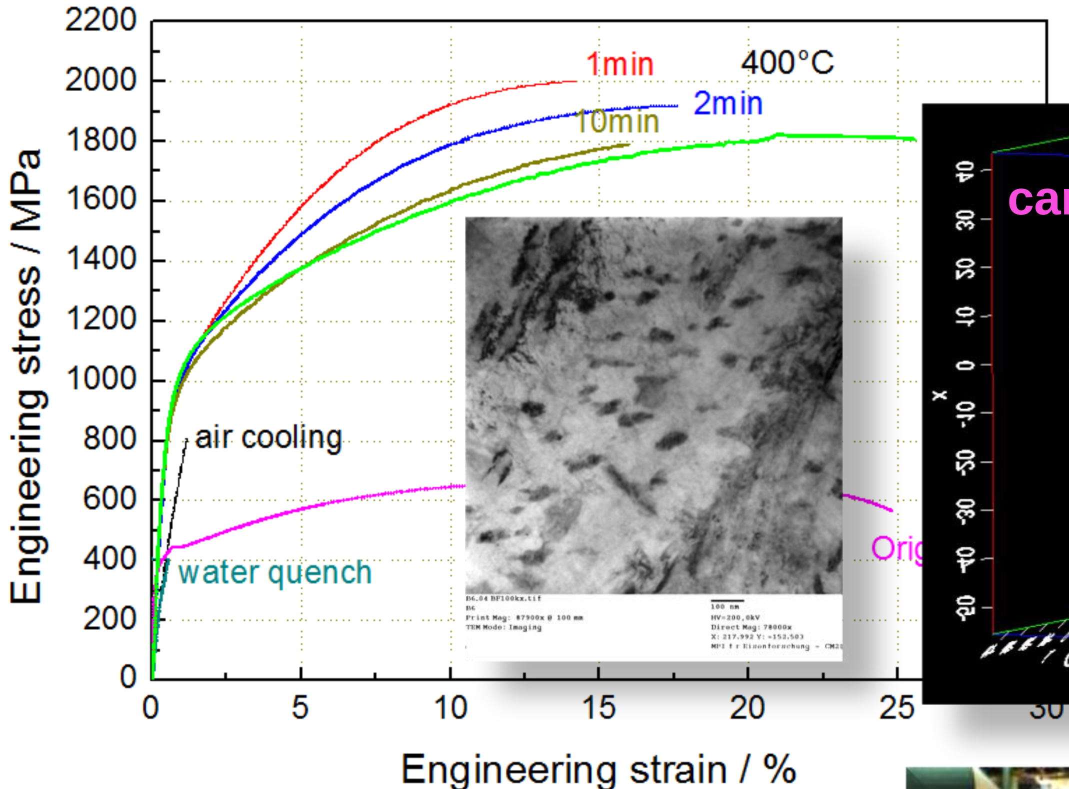
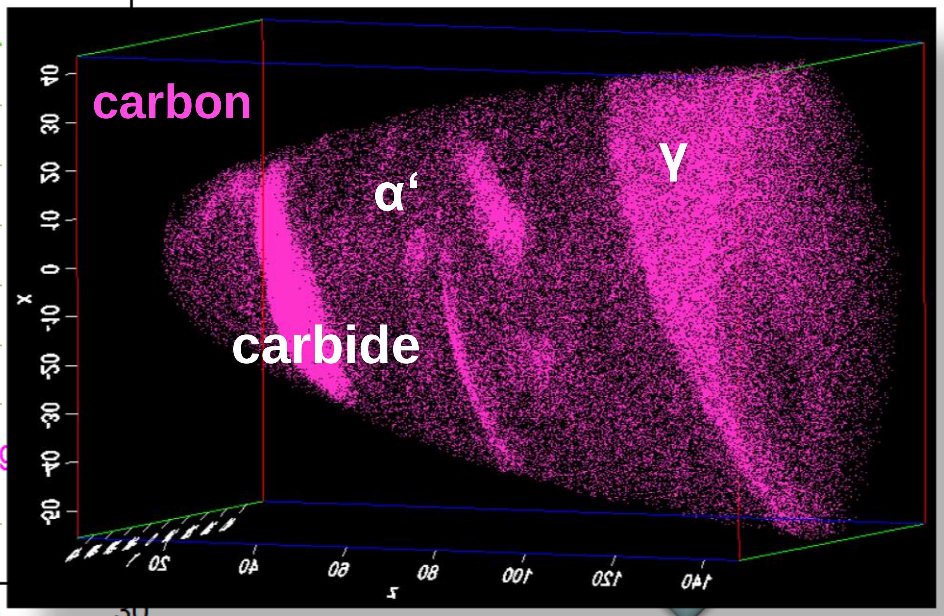
Example # 2– key mechanisms: Martensite relaxation and aging

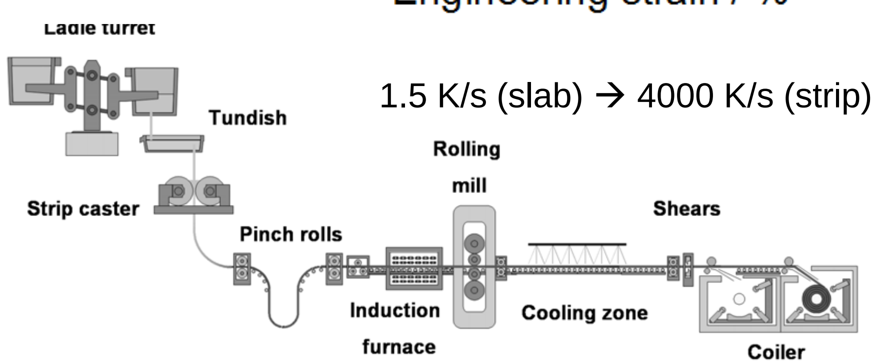
2 GPa-steels: Aged martensite: Fe 13 Cr > 0.3 C

Ultra high strength and corrosion resistance





1.5 K/s (slab) → 4000 K/s (strip)



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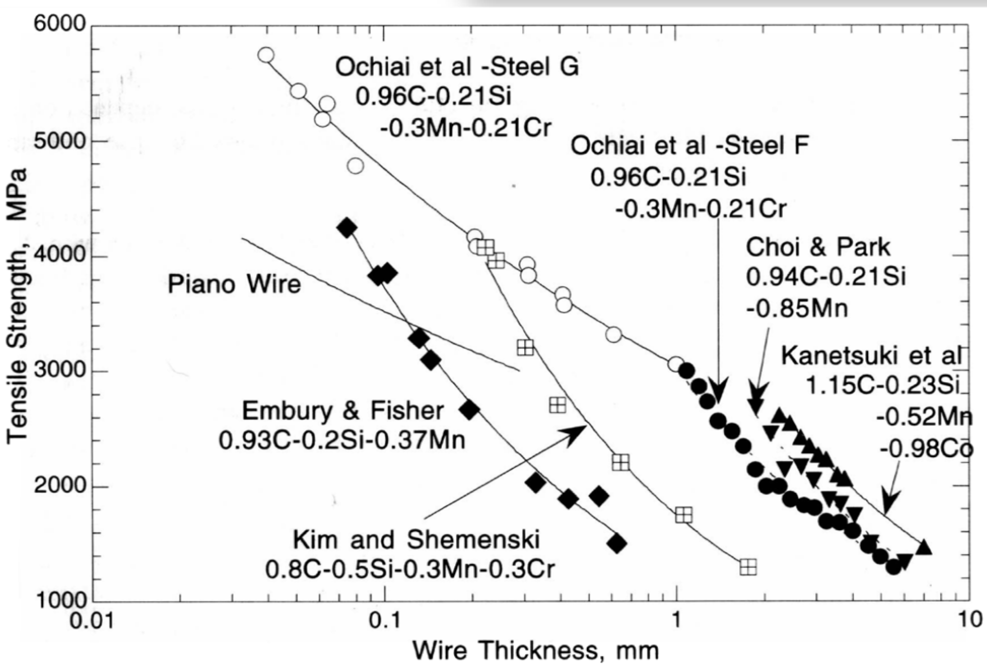
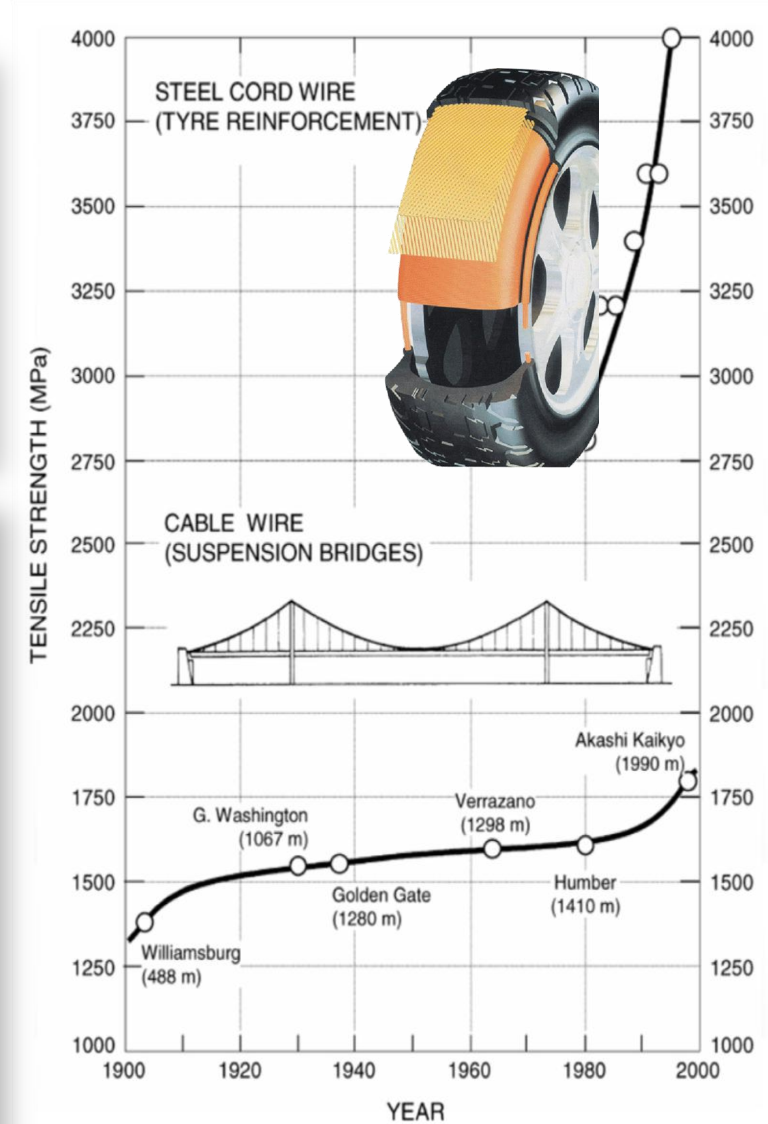
Pearlite: Laminate nanostructures

> 5 GPa-steels:
Pearlite:
nanostructured and
mechanically alloyed

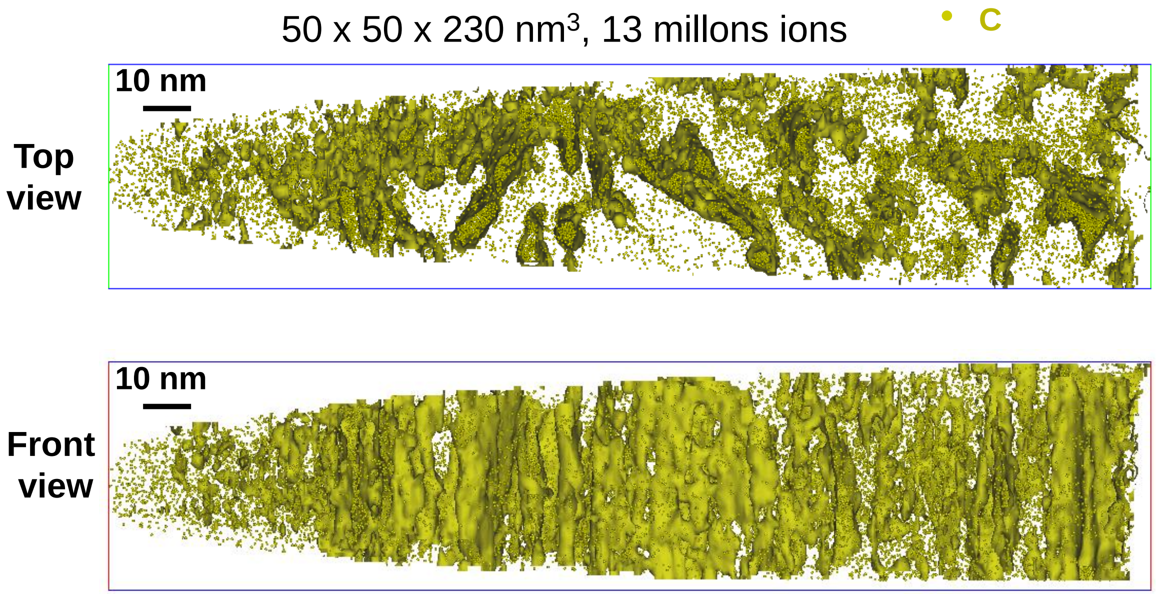




Data from Lesuer, Syn, Sherby and Kim, Metallurgy, Processing and Applications of metal wires, TMS, 1993; M.H. Hong, W.T. Reynolds, Jr., T. Tarui, K. Hono, Metall. Mater. Trans. A 30, 717 (1999); T. Tarui, N. Maruyama, J. Takahashi, S. Nishida, H. Tashiro, Nippon Steel Technical Report 91, 56 (2005); S. Goto, R. Kirchheim, T. Al-Kassab, C. Borchers, Trans. Nonferrous Met. Soc. China 17, 1129 (2007); J. Takahashi, T. Tarui, K. Kawakami, Ultramicroscopy 109, 193 (2009); A. Taniyama, T. Takayama , M. Arai, T. Hamada, Scripta Mater. 51, 53 (2004); [6] K. Hono, M. Ohnuma, M. Murayama, S. Nishida, A. Yoshie, Scripta Mater. 44, 977 (2001).

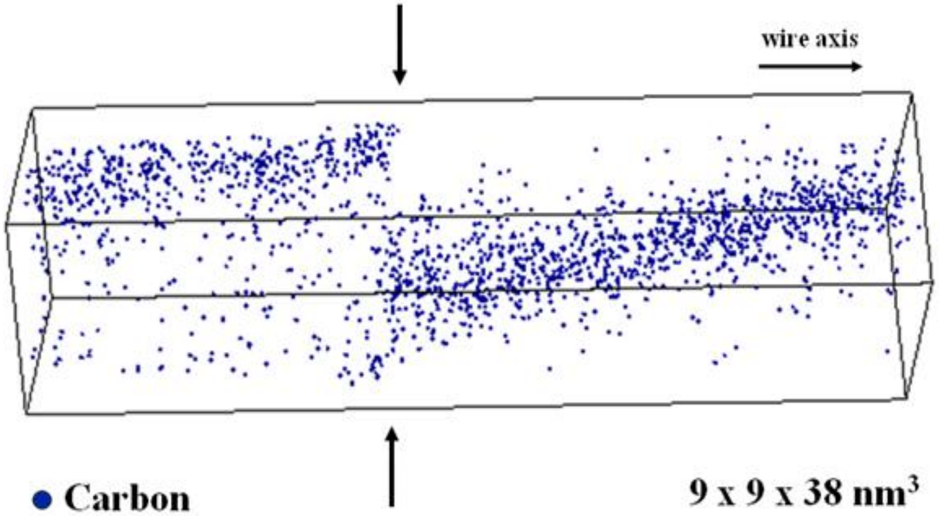
Pearlite, chemical composition and 3D reconstructed atom map

50 x 50 x 230 nm^3, 13 millons ions



Iso-concentration value 7 at. % C

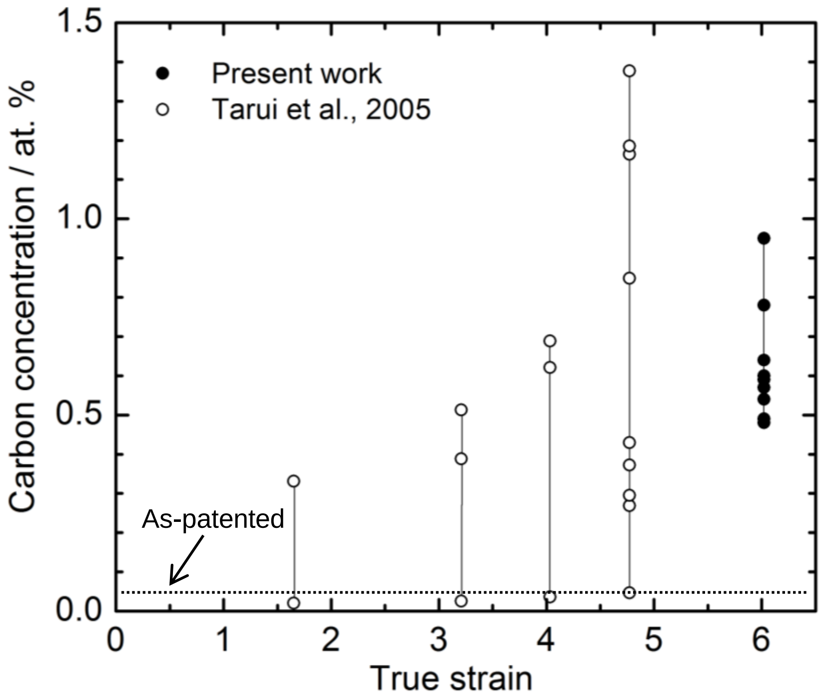
Sauvage: sharp steps in the mechanical alloying profile. pearlite



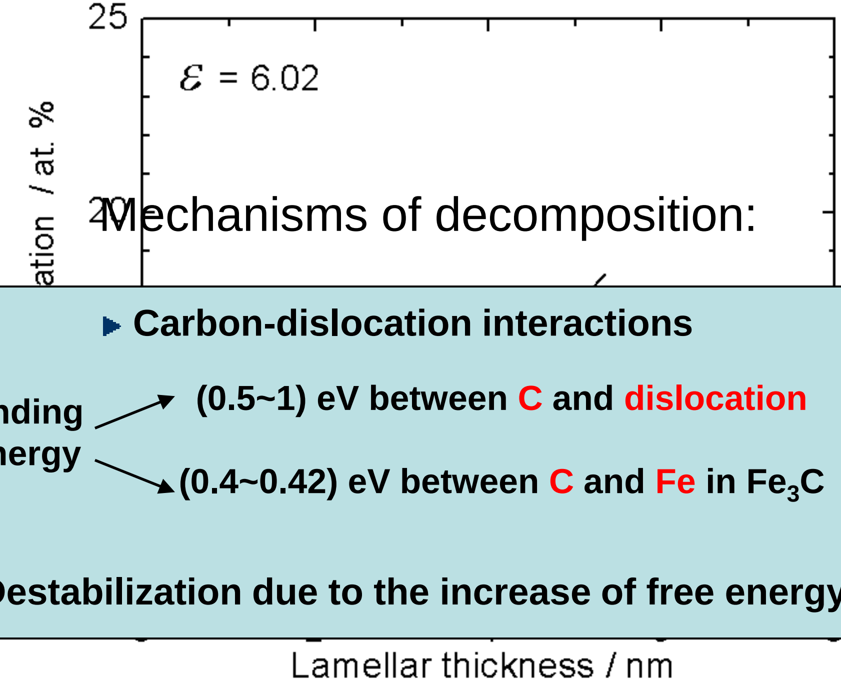
data: Xavier Sauvage, Rouen

Pearlite, chemical composition as a function of strain and size

Ferrite



Cementite



Mechanisms of decomposition:

- **Carbon-dislocation interactions**

Binding energy
- **(0.5~1) eV between C and dislocation**
- **(0.4~0.42) eV between C and Fe in Fe_3C**

- **Destabilization due to the increase of free energy**

1. **Large amount of C dissolved in ferrite**
2. **Inhomogeneous distribution of C**

- **Carbon concentration as fct. of lamellar thickness**

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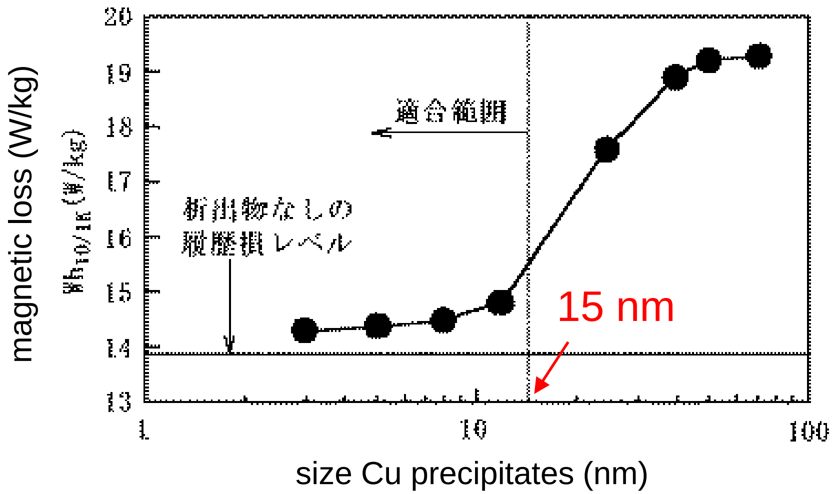


{JP 2004 339603}

nanoparticles too small for Bloch-wall interaction but effective as dislocation obstacles

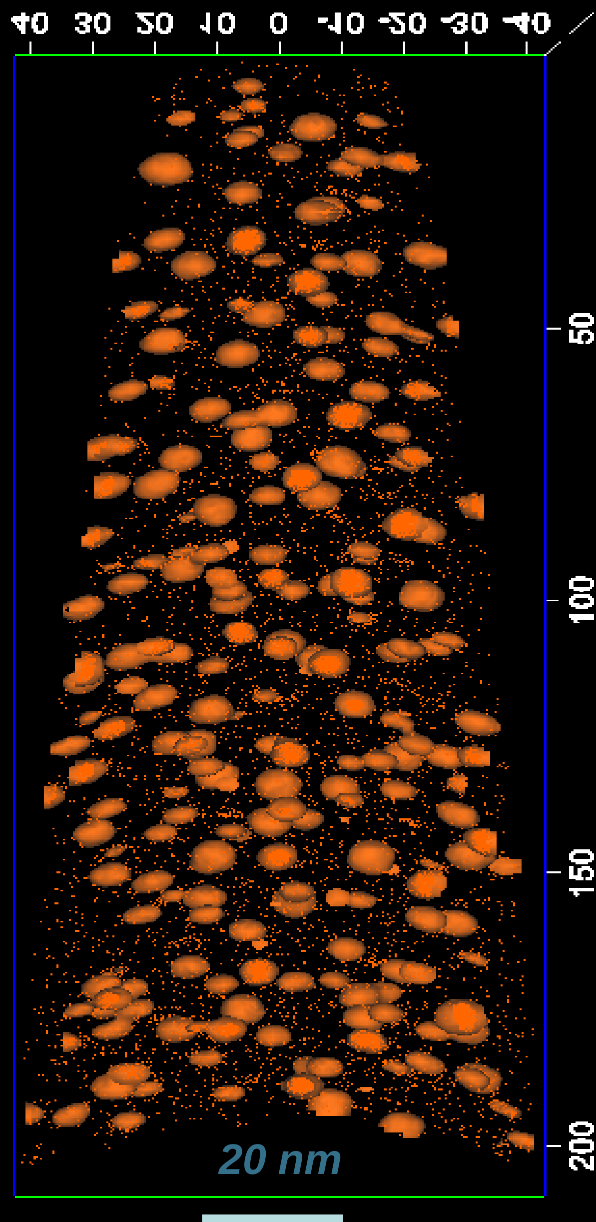
mechanically very strong soft magnets for motors

Cu 2 wt.%

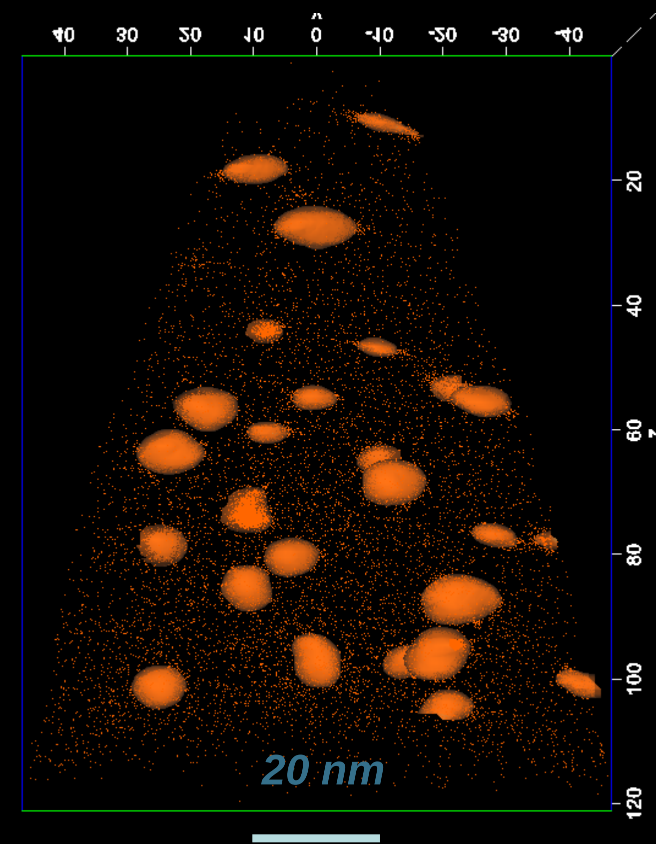
450°C **aging**

Iso-concentration surfaces for Cu 11 at.%

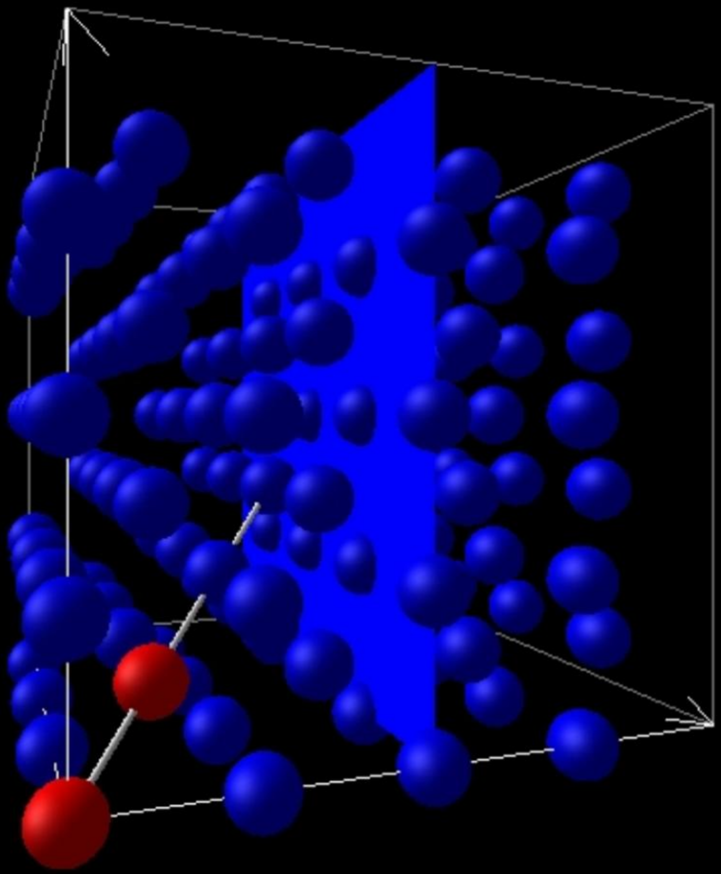
120 min



6000 min



Modeling: ab-initio, DFT / GGA, binding energies



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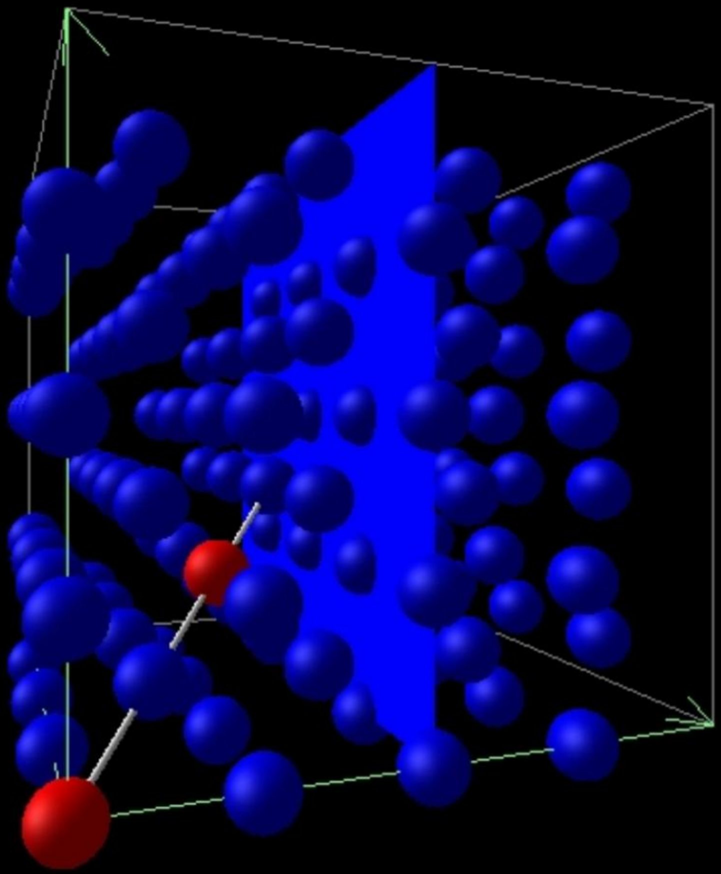

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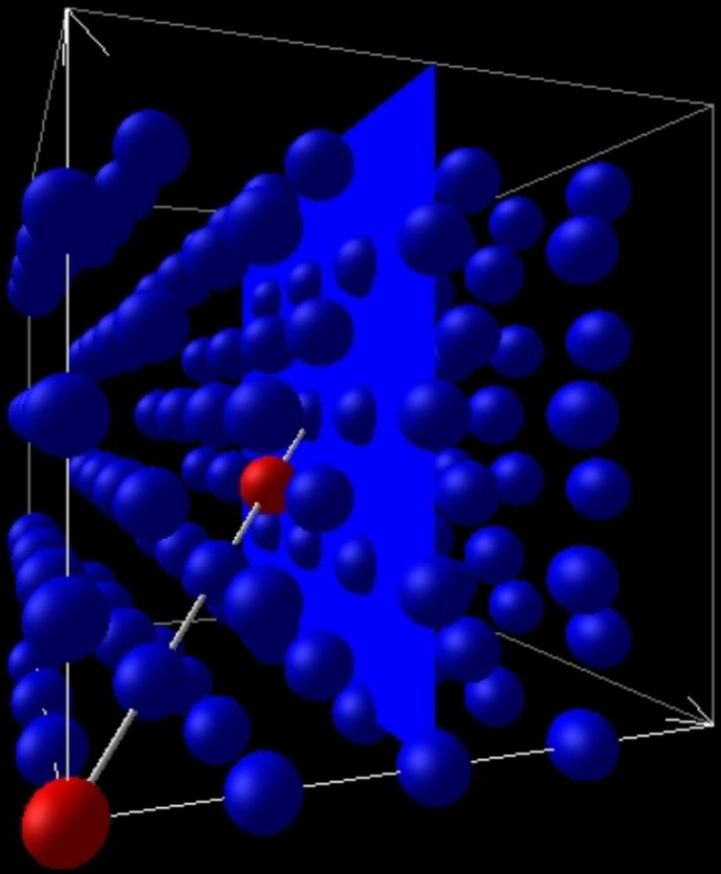

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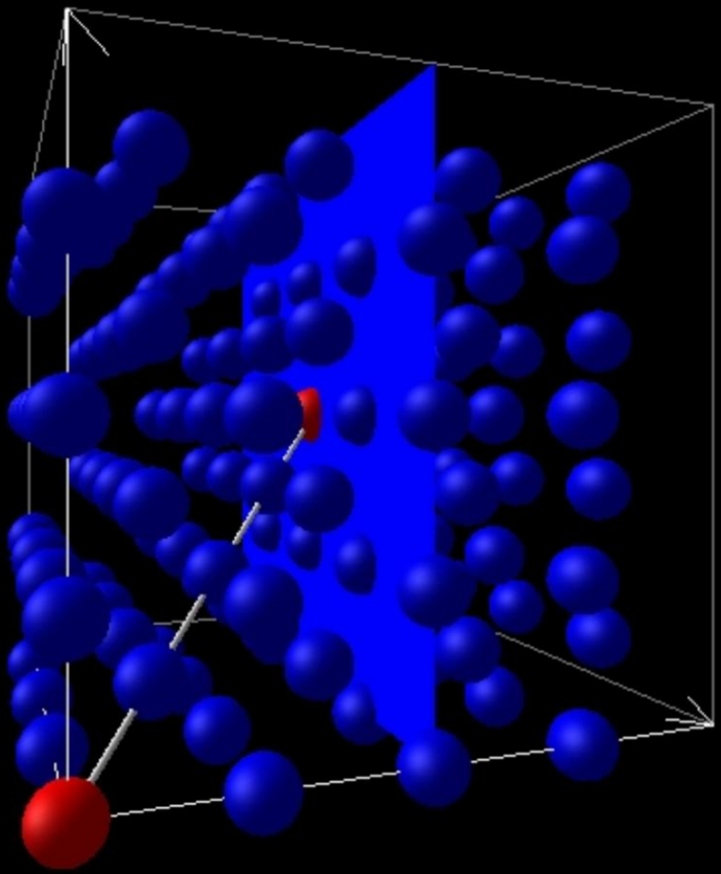
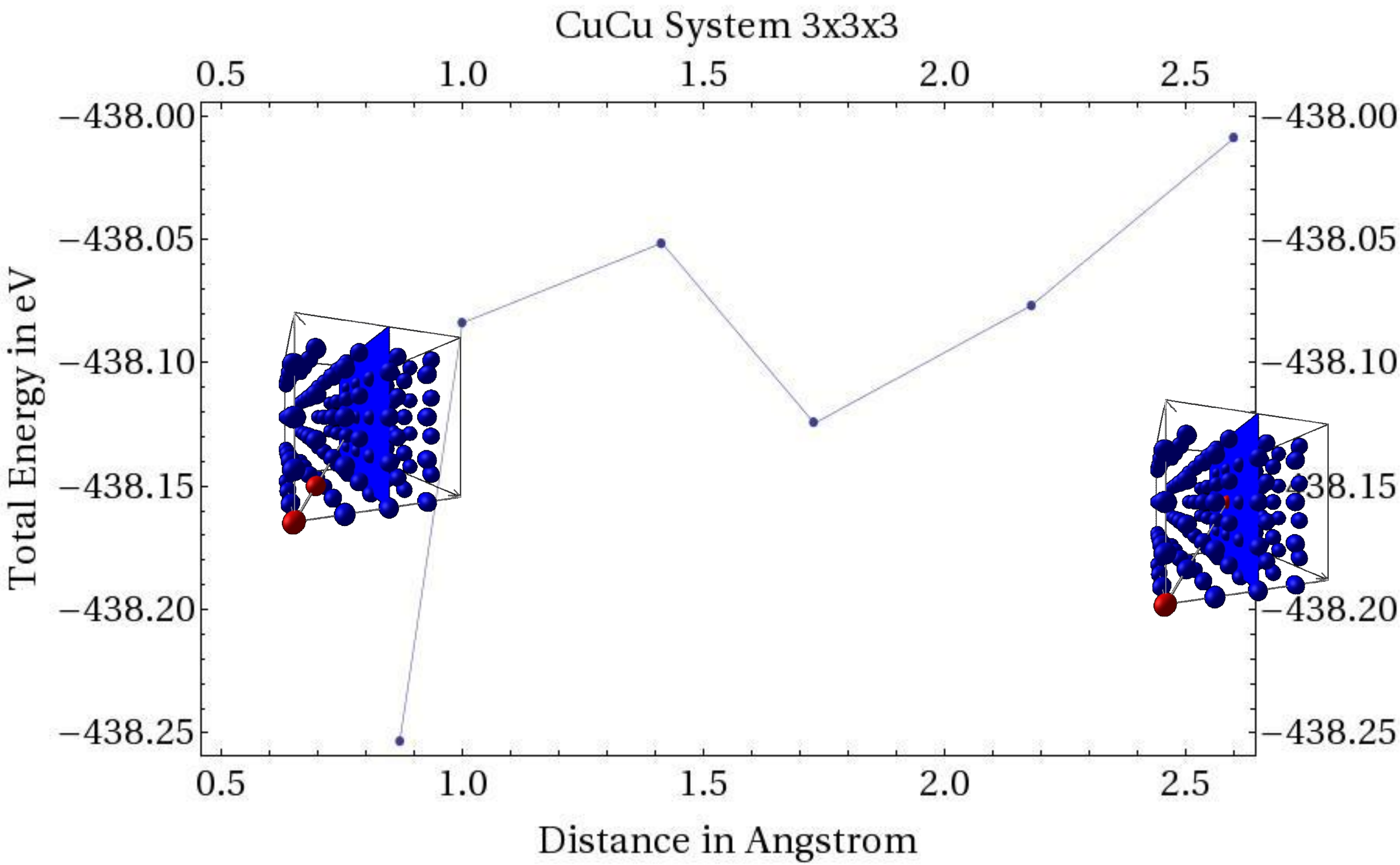
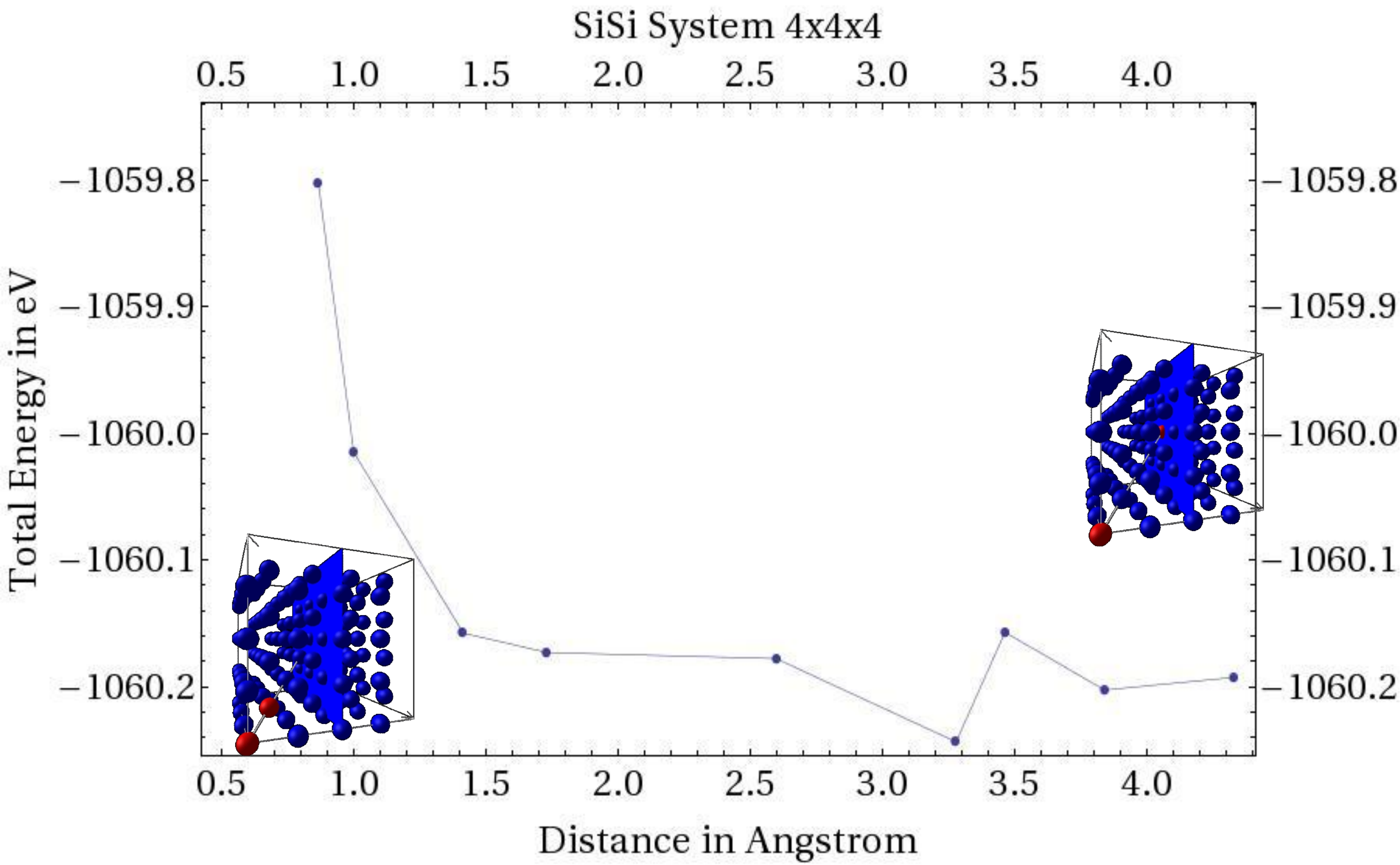


Ab-initio, binding energies: Cu-Cu in Fe matrix



Ab-initio, binding energies: Si-Si in Fe matrix



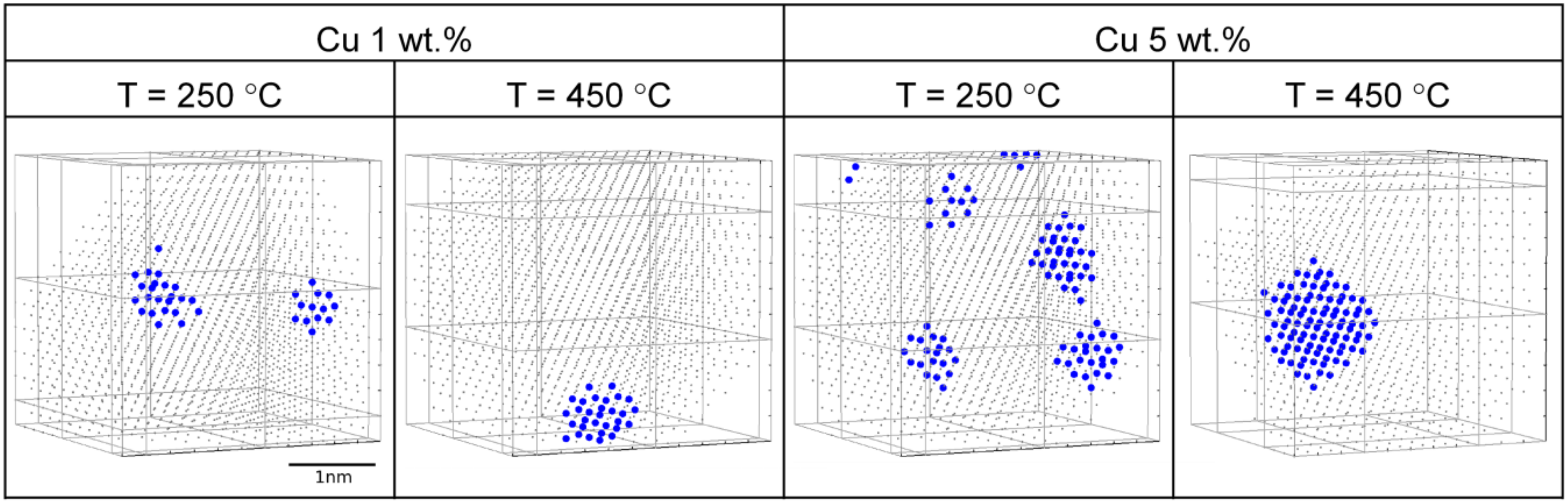
For neighbor interaction energy take difference (in eV)

E^{bin}_{SiSi} (repulsive) = 0.390

E^{bin}_{SiCu} (attractive) = -0.124

E^{bin}_{CuCu} (attractive) = -0.245

Ab-initio, use binding energies in kinetic Monte Carlo model



There are about 40 million cars in Germany

High strength soft magentic steels in car engines and transfomers reduce CO_2 emission