Designing strong and ductile alloys

Intrinsic Bulk Nanostructuring via Confined Phase Transformation

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Department for Microstructure Physics and Alloy Design

Structure of the Department

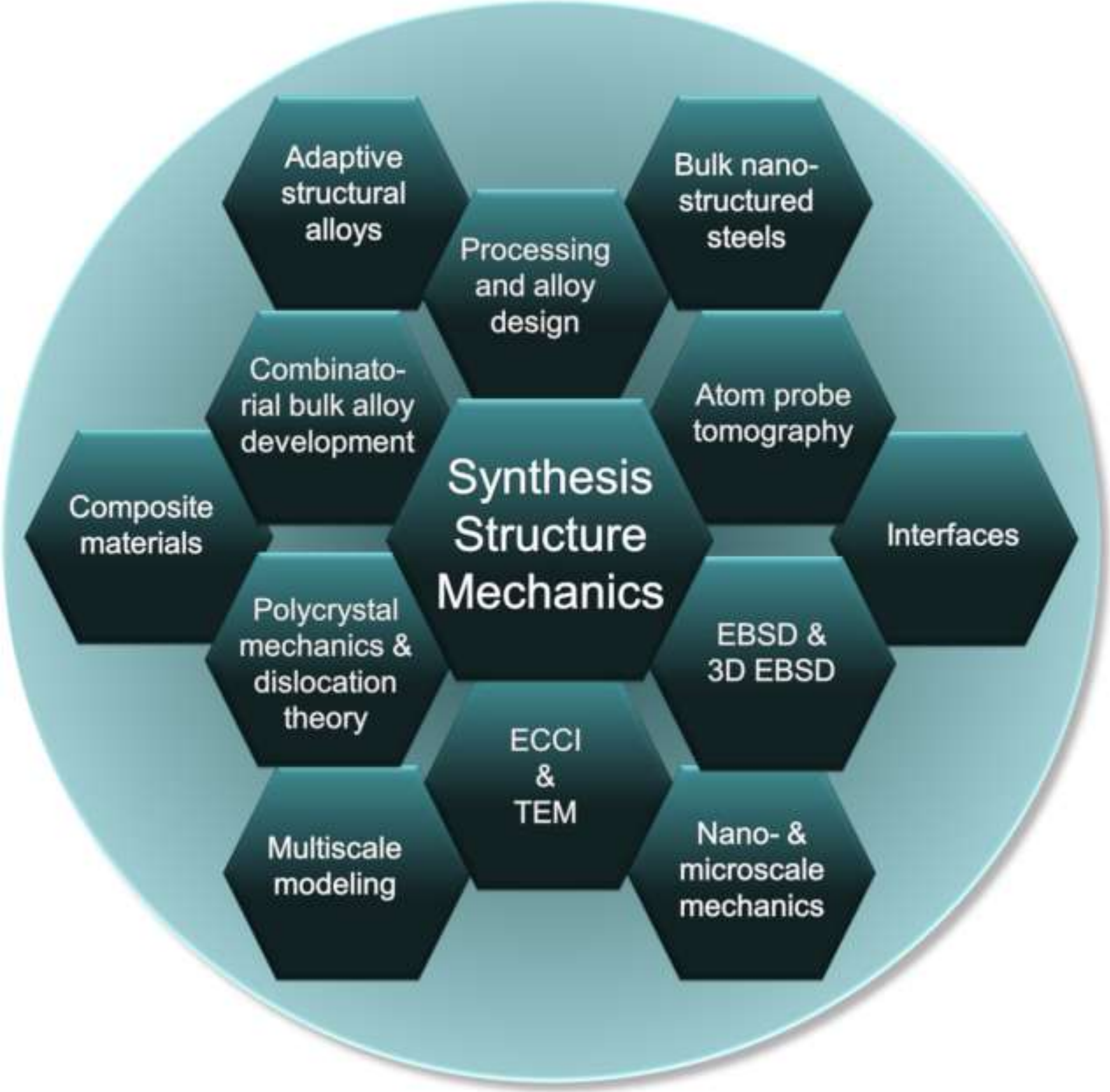
Department for Microstructure Physics and Alloy Design

Dierk Raabe

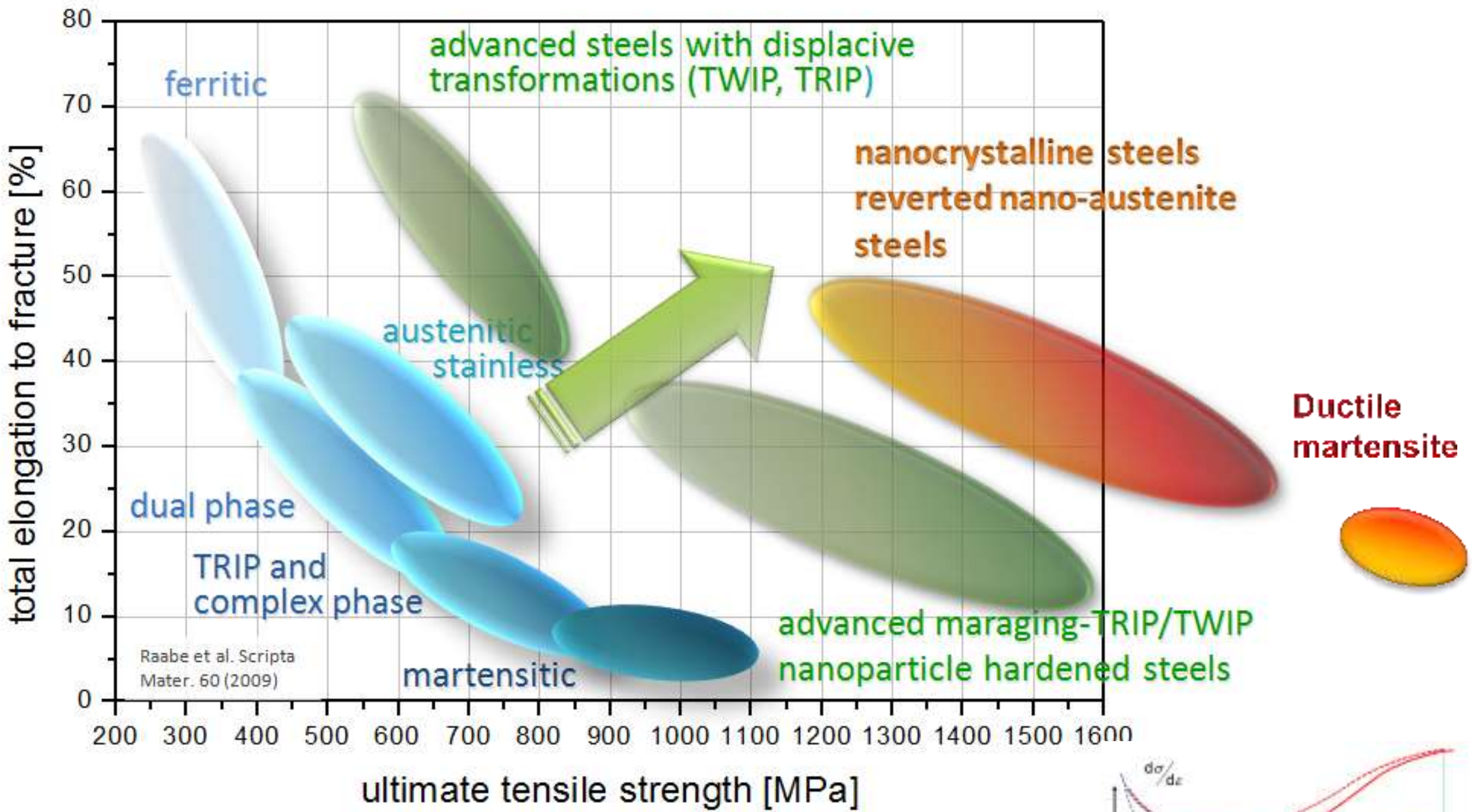
				New MPI group	Funded by Leibniz Award	Funded by ERC Advanced Grant
Dirk Ponge	**Franz Roters**	**Stefan Zaefferer**	**Helge Fabritius**	**Hauke Springer**	**Pyuck-Pa Choi**	**Cem Tasan**
Alloy Design & Thermomech. Processing	*Theory & Simulation*	*Diffraction & Microscopy*	*Mechanics of Bio-Composites*	*Combinatorial Metallurgy & Processing*	*Atomic-Scale Spectroscopy*	*Adaptive Structural Materials*
new alloys *UFG alloys* *themomechical* *Steel microstructure*	*materials Mechanics* *process models* *crystal plasticity* *transformation modeling*	*textures* *EBSD* *TEM* *3D EBSD* *in-stu SEM*	*biomaterials* *polymers* *biological Materials* *bone, chitin, teeth*	*rapid alloy Prototyping* *advanced structural Materials* *welding*	*tomographic atom probe* *functional materials* *Nanostructures*	*alloy design* *mesoscale in situ characteri-sation* *instable phases*

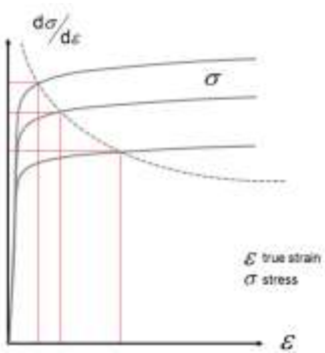
Services: metallography, computer services, materials testing, materials technology

Structure of the Department

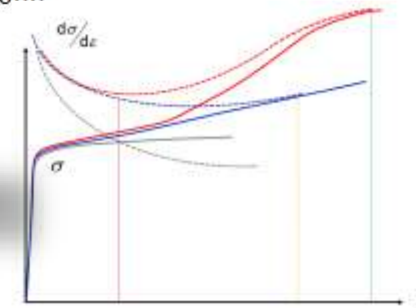


Local phase transformations enable high strength of bulk metals

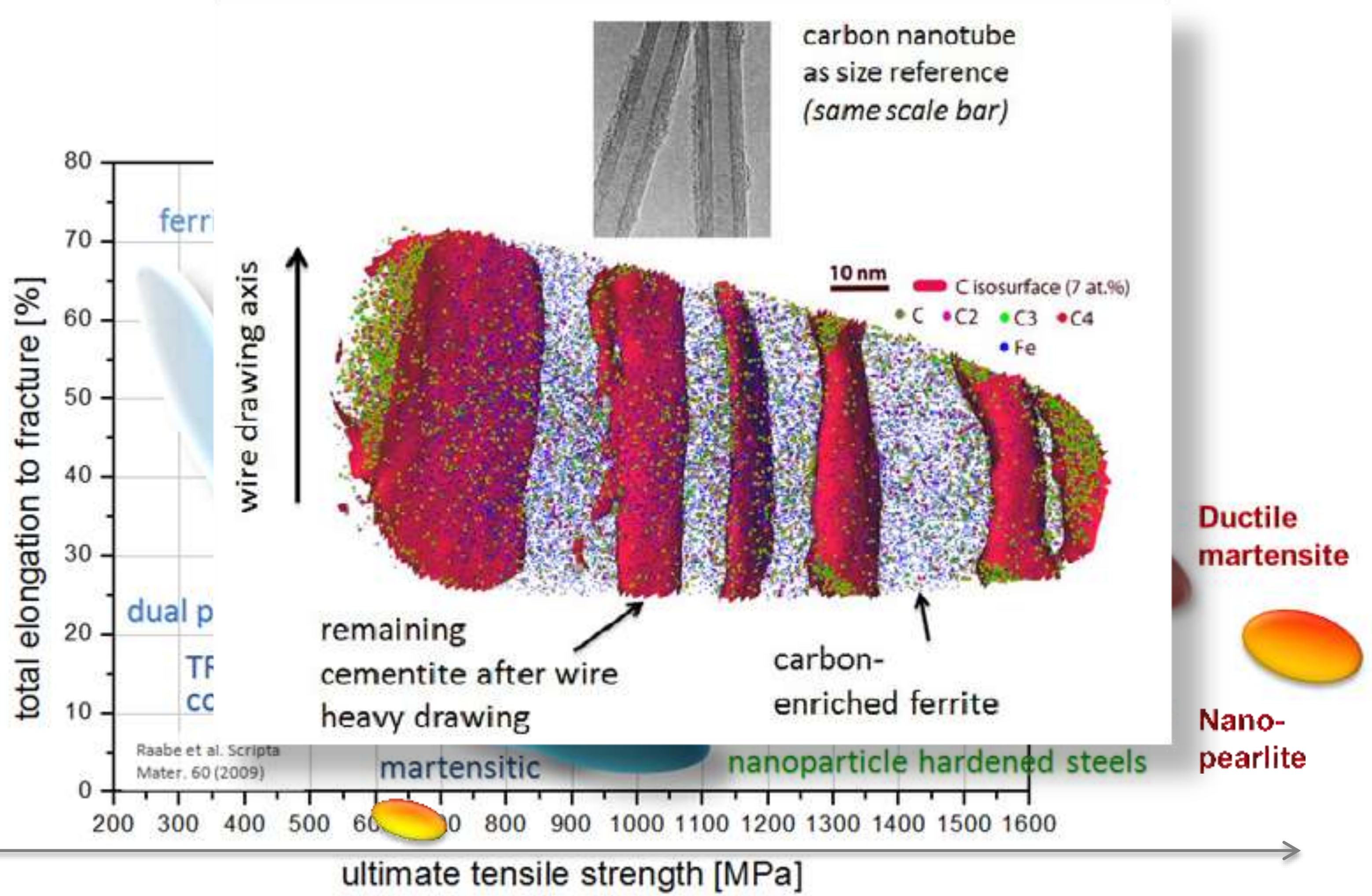




Inverse strength-ductility relation



Design strain hardening only where needed


carbon nanotube
as size reference
(same scale bar)
10 nm
C isosurface (7 at.%)
C
C2
C3
C4
Fe
wire drawing axis
remaining
cementite after wire
heavy drawing
carbon-
enriched ferrite
total elongation to fracture [%]
80
70
60
50
40
30
20
10
0
ferri
dual p
TF
cc
Raabe et al. Scripta
Mater. 60 (2009)
martensitic
nanoparticle hardened steels
Ductile
martensite
Nano-
pearlite
200
300
400
500
60
0
800
900
1000
1100
1200
1300
1400
1500
1600
ultimate tensile strength [MPa]

> 6 GPa

Examples

Pearlite: the limits of strength

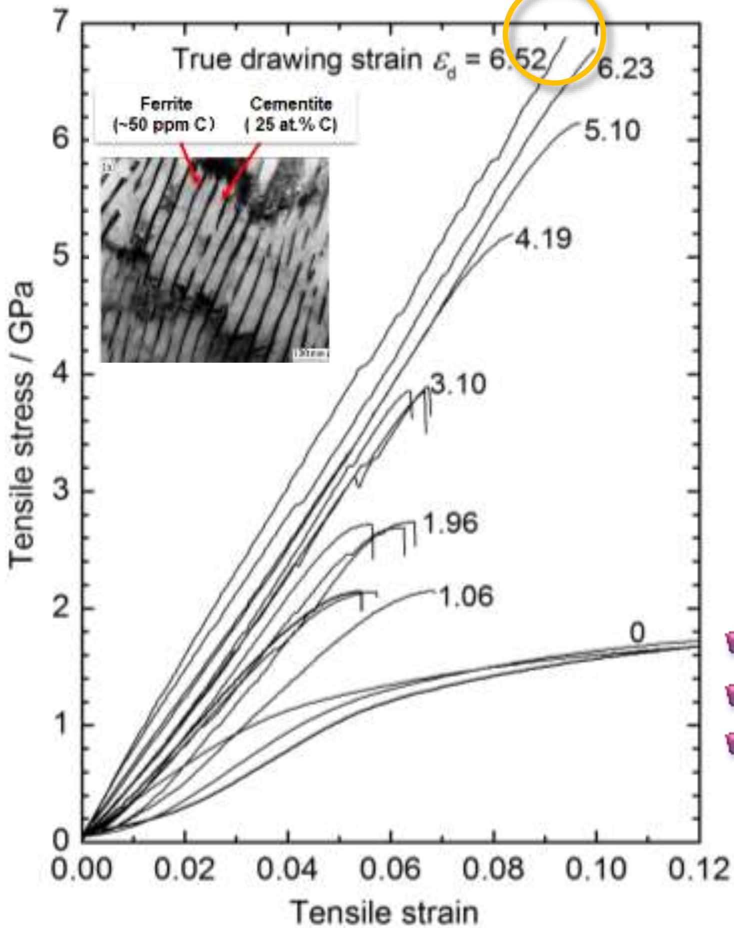
Nano-austenite reversion

Nanotwinning

Fe-based superalloy

Towards the limits of strength and strain hardening

~7 GPa



strength of blade martensite

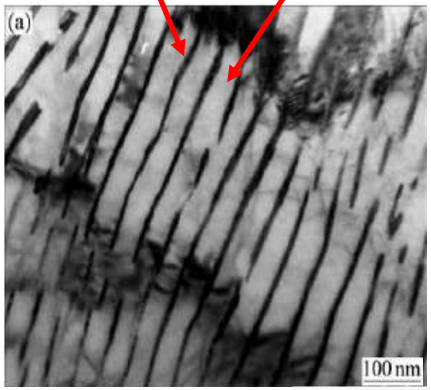
strength of TWIP

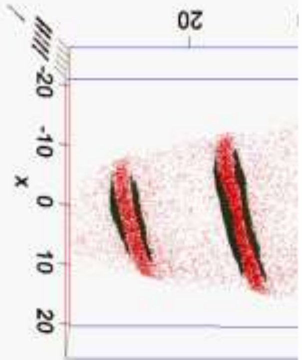
strength of spider silk

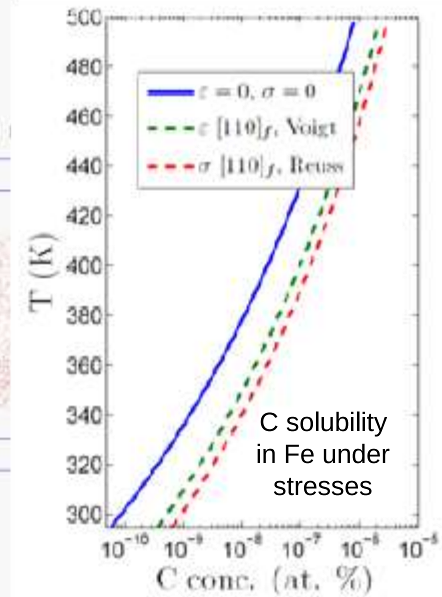
Cooperation:
Neugebauer
Kirchheim

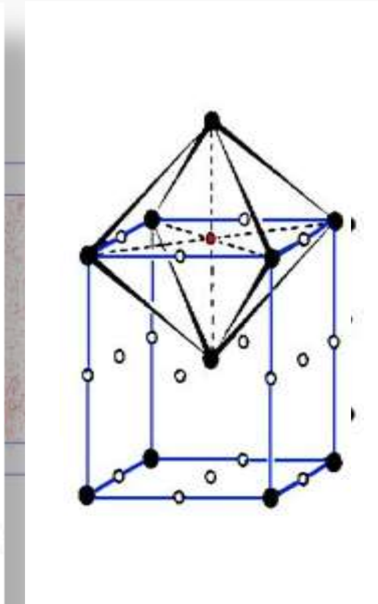
Towards the limits of strength: cold-drawn pearlitic steel

Ferrite (~50 ppm C) | **Cementite** (25 at.% C)







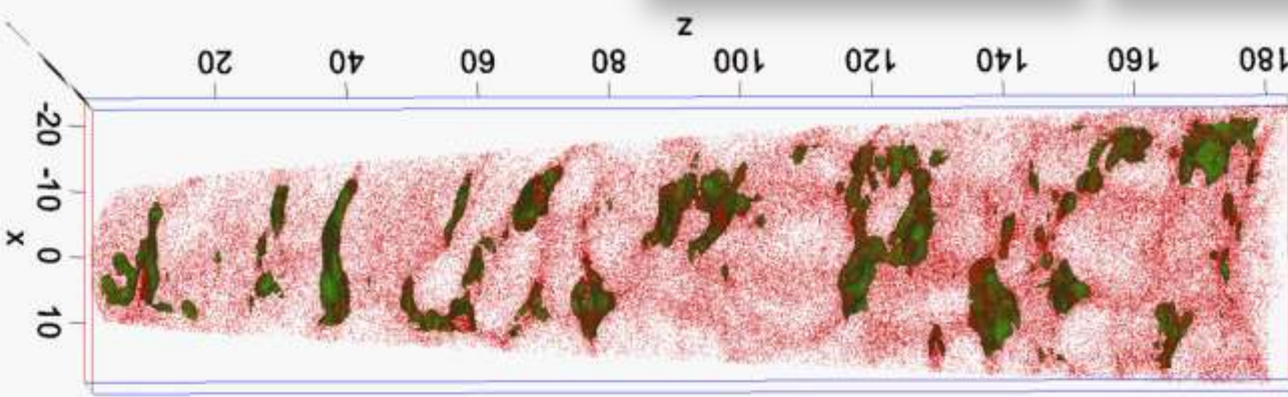


= 2)

ale: nm

C iso-concentration (7 at.%)

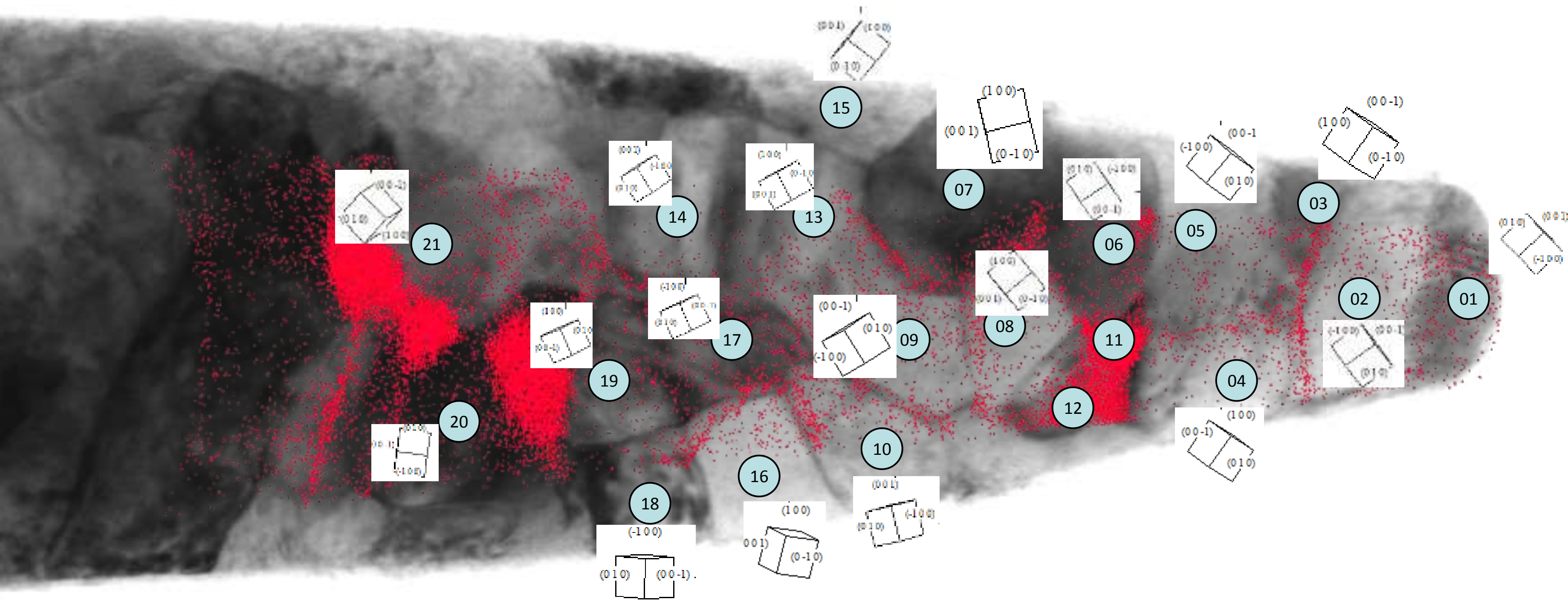
• C



(ε = 6.5)

Cooperation:
Neugebauer
Kirchheim

Structure and composition at grain boundaries: pearlite



• C

→ lecture by Michael Herbig

→ poster by Li and Kirchheim

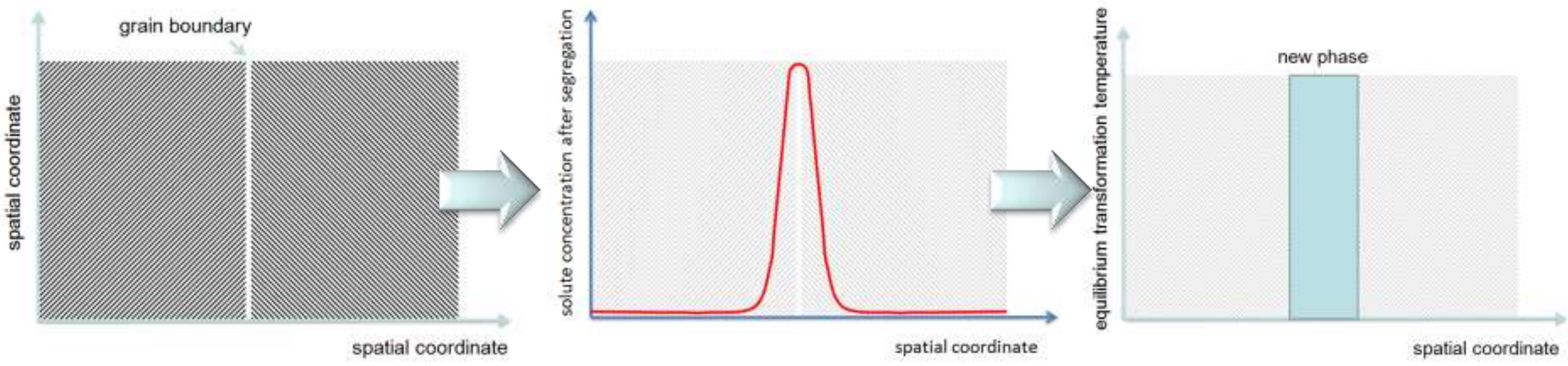
Pearlite: the limits of strength

Nano-austenite reversion

Nanotwinning

Fe-based superalloy

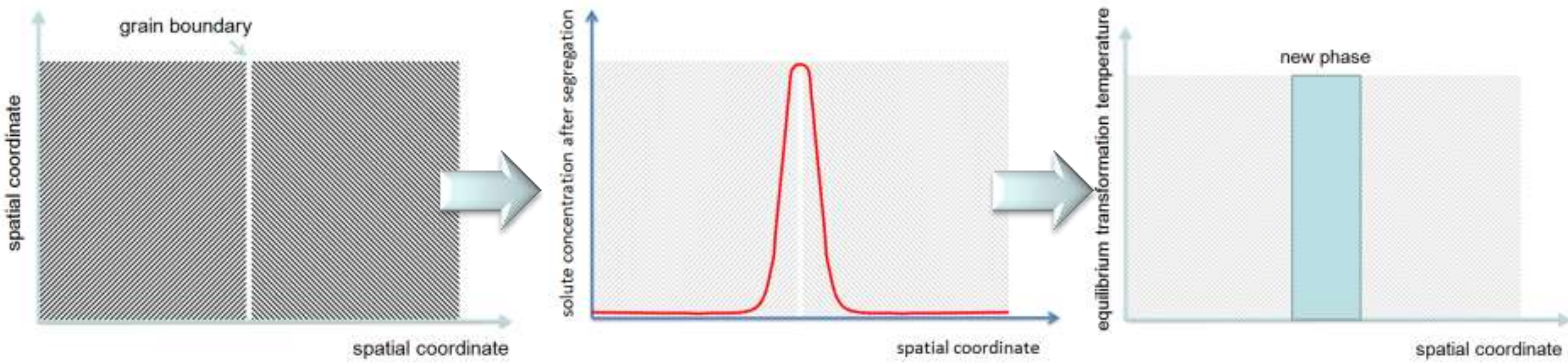
Segregation Engineering: nanostructuring by transformation



Solute segregation to martensite grain boundaries

Local phase transformation at grain boundary
(martensite-to-austenite reversion confined to GB)

Self-organized nanostructuring by selective phase transformation



Solute segregation to martensite grain boundaries

- Element with high segregation tendency
- Reduce transformation temperature (e.g. from martensite to austenite)
- Prefer segregation over bulk precipitation (e.g. carbide)

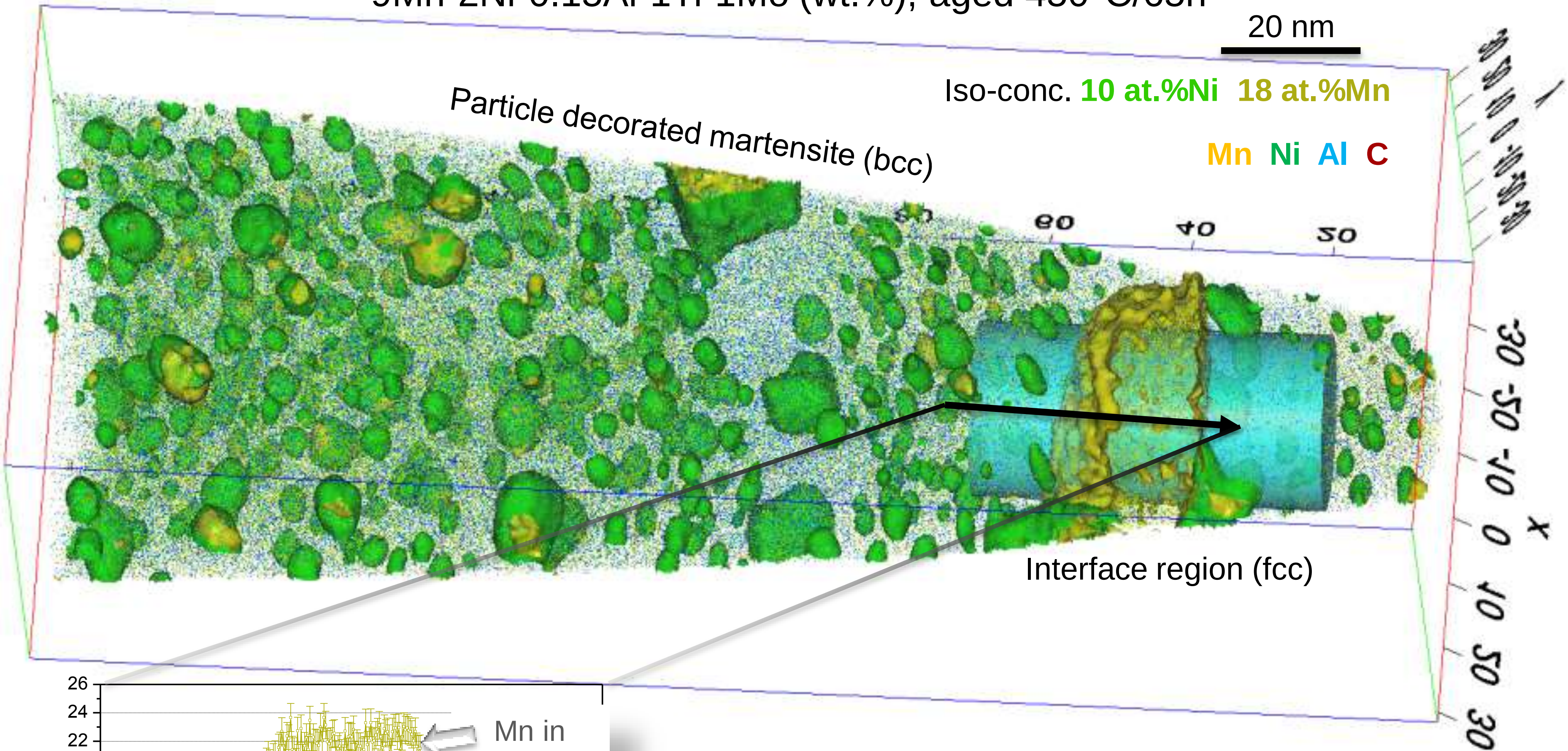
Local phase transformation at grain boundary (martensite-to-austenite reversion confined to GB)

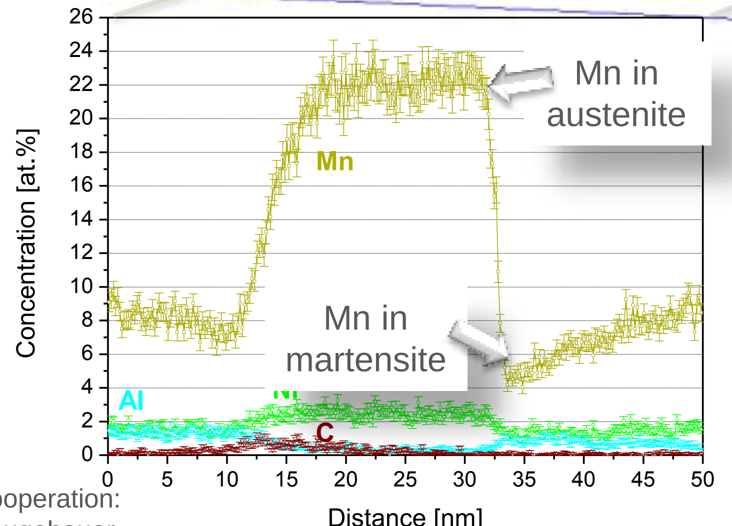
Struture and composition at grain boundary: Mn09, 450°C/10 min

Grain boundary <111> 6-7°

Mn

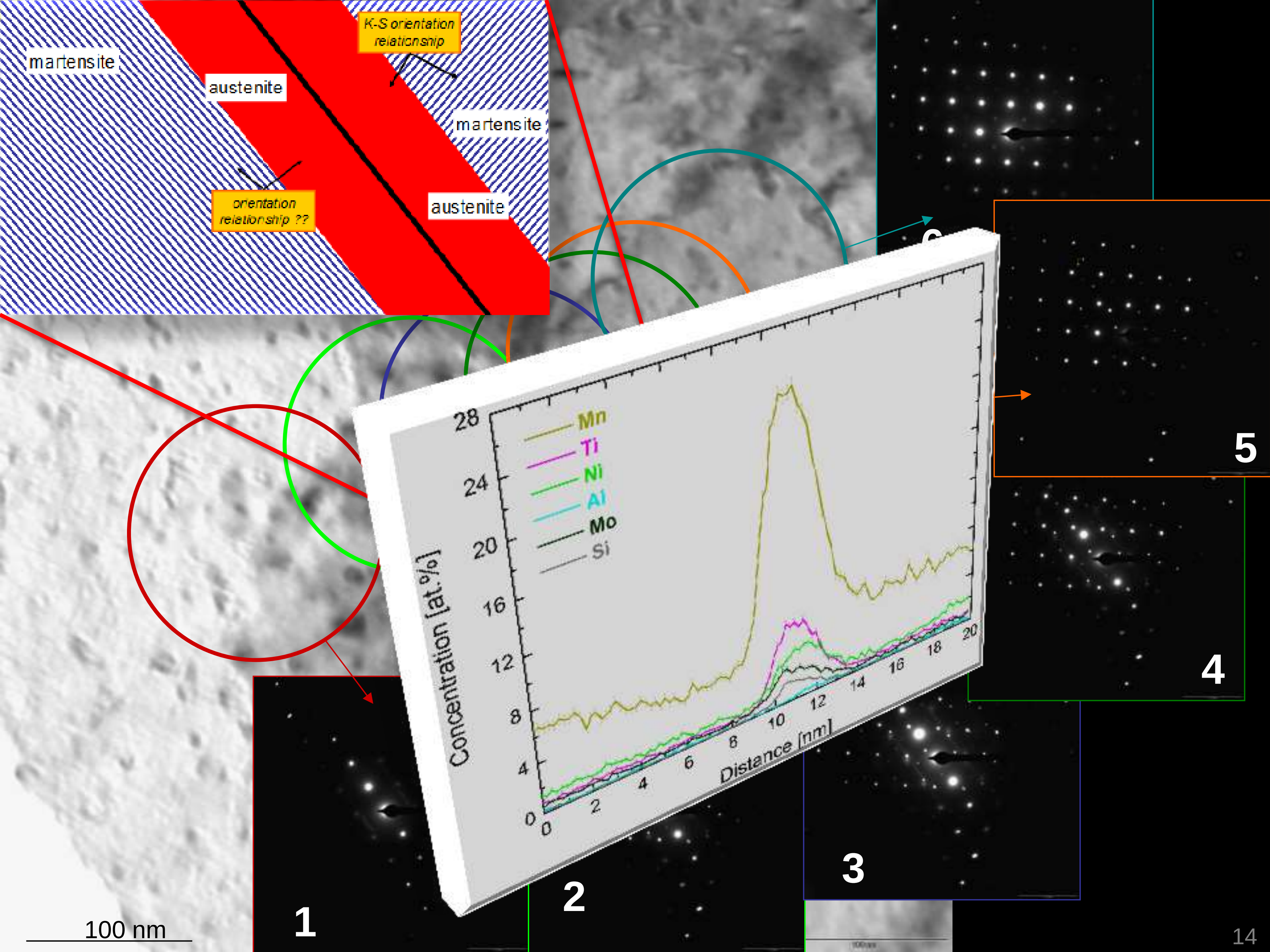
9Mn-2Ni-0.15Al-1Ti-1Mo (wt.%), aged 450°C/65h



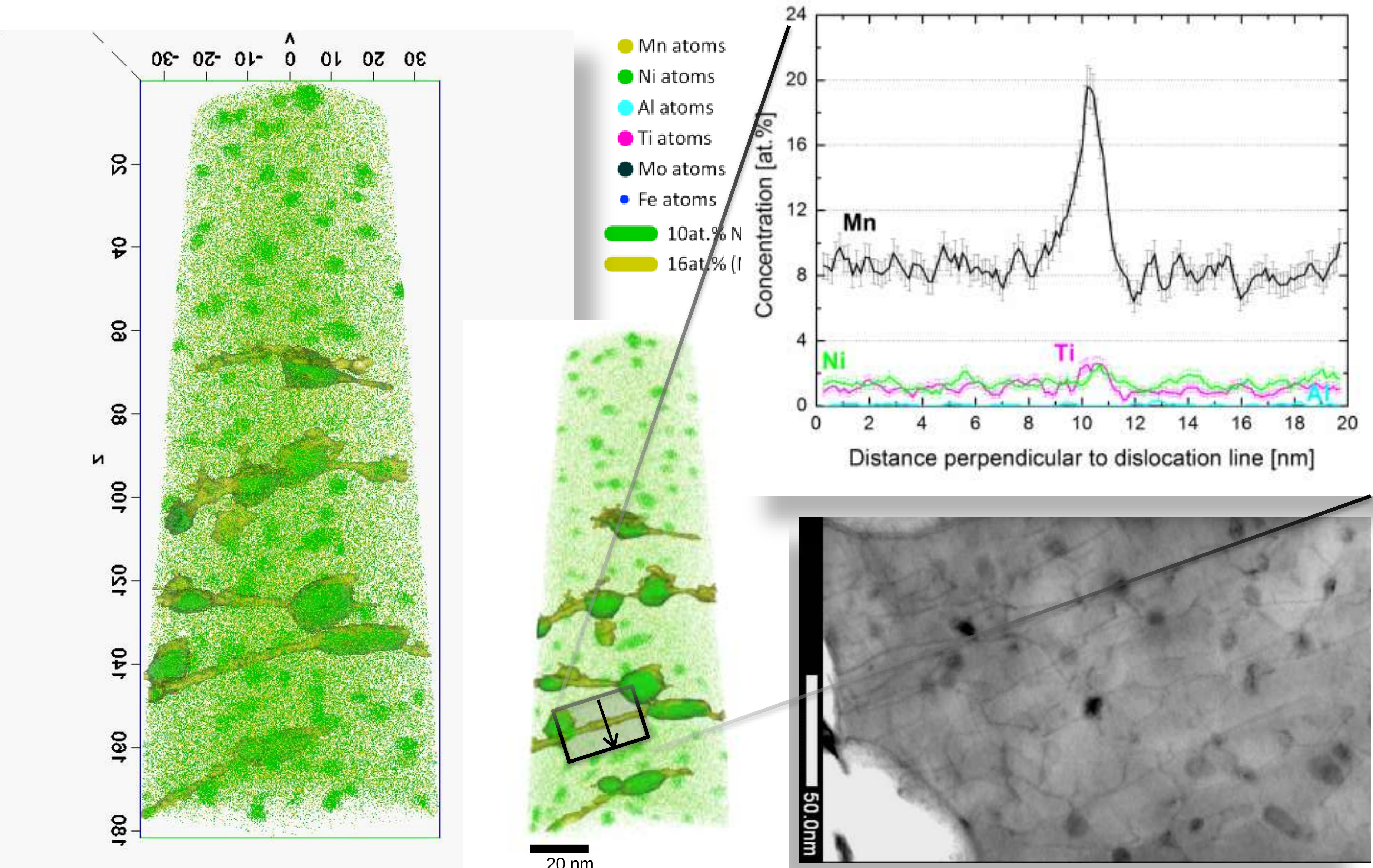


Phase formation at martensite interface
Near equilibrium partitioning at interface

Cooperation:
Neugebauer


martensite
austenite
K-S orientation relationship
martensite
austenite
orientation relationship ??
Mn
Ti
Ni
Al
Mo
Si
Concentration [at.%]
Distance [nm]
1
2
3
4
5
100 nm

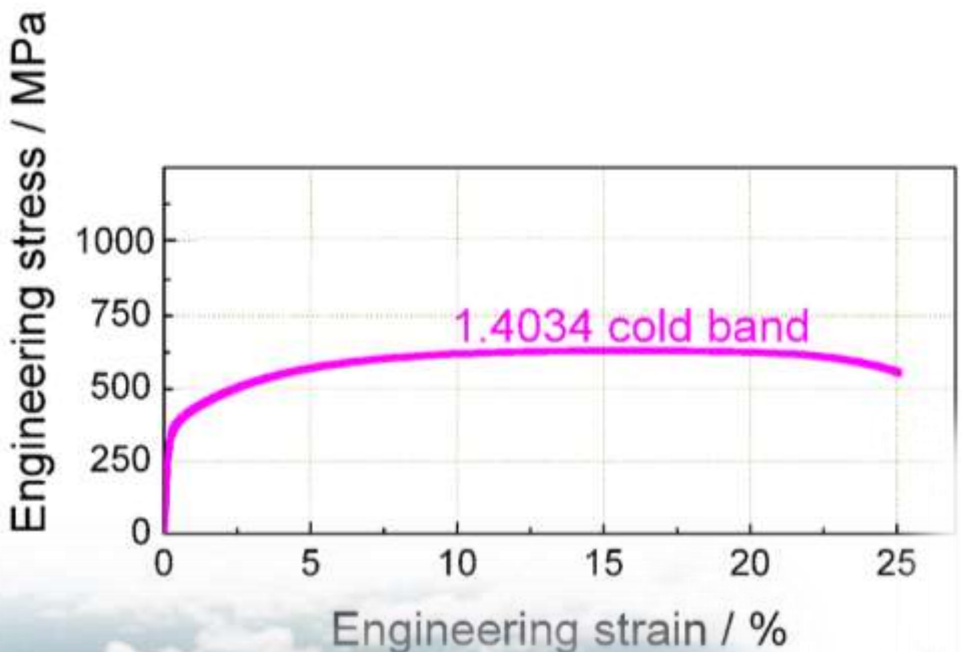
Same effect even at dislocations ?

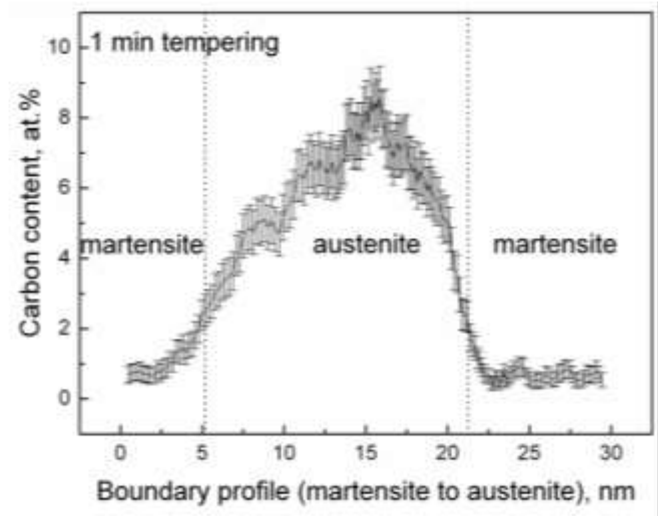


Martensite relaxation & aging & nanoscale austenite reversion

650 MPa to 2 GPa

Making martensite ductile





Fe-13.6Cr-0.44C (wt.%)

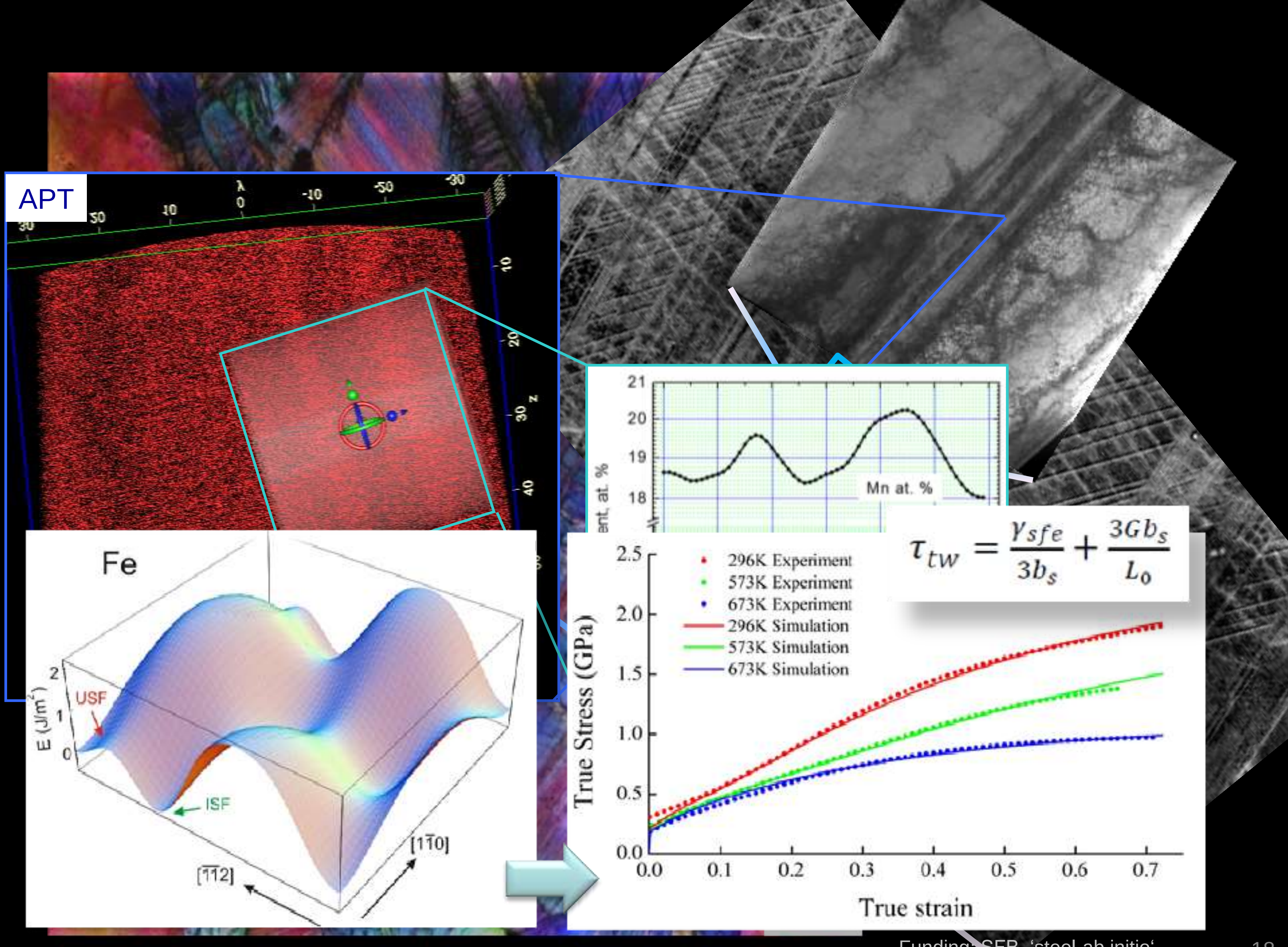
Examples

Pearlite: the limits of strength

Nano-austenite reversion

Nanotwinning

Fe-based superalloy



$$\tau_{tw} = \frac{\gamma_{sfe}}{3b_s} + \frac{3Gb_s}{L_0}$$

Funding: SFB 'steel-ab initio'

Examples

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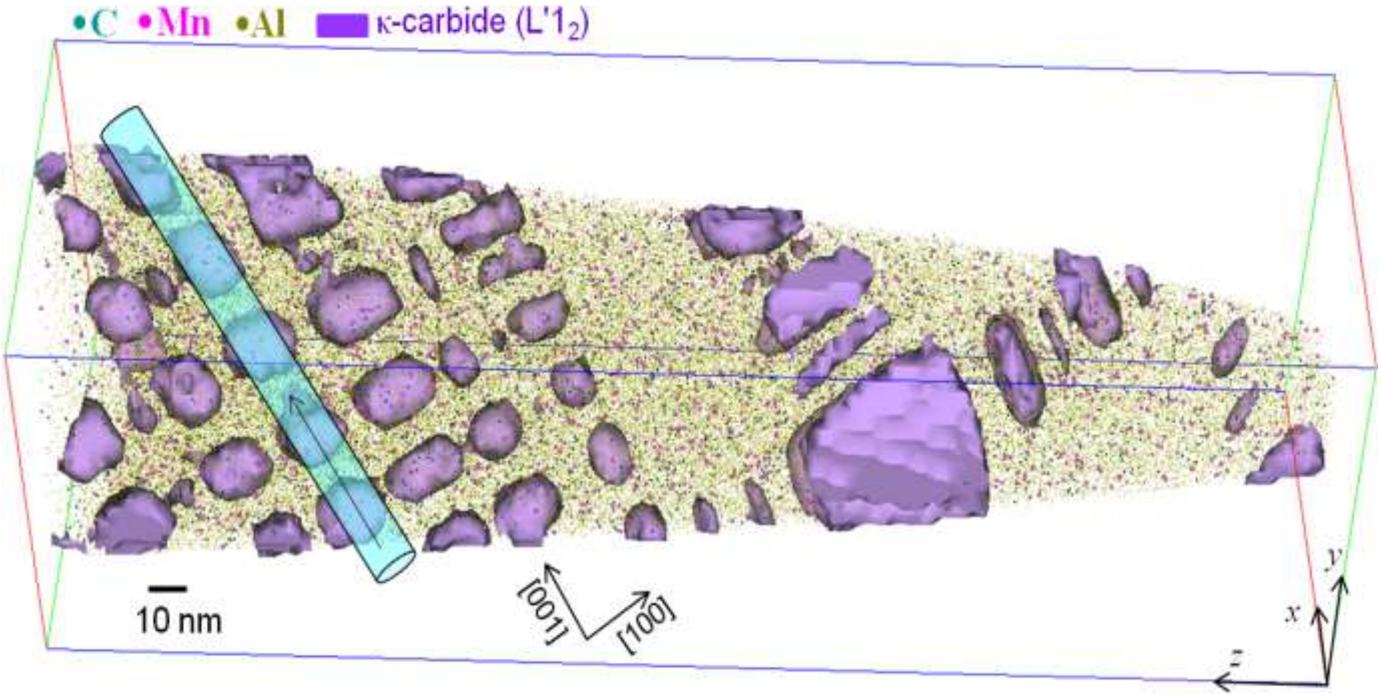
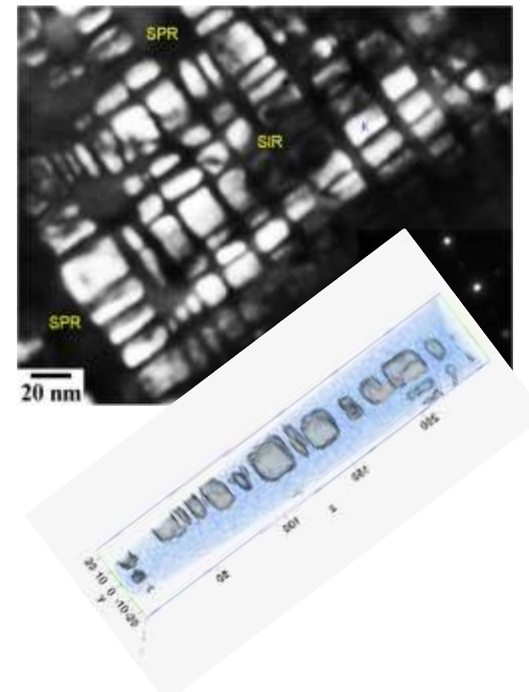
Fe-based superalloy

Fe-30%Mn-8%Al-1.2%C weight reduced alloys (10% less density)

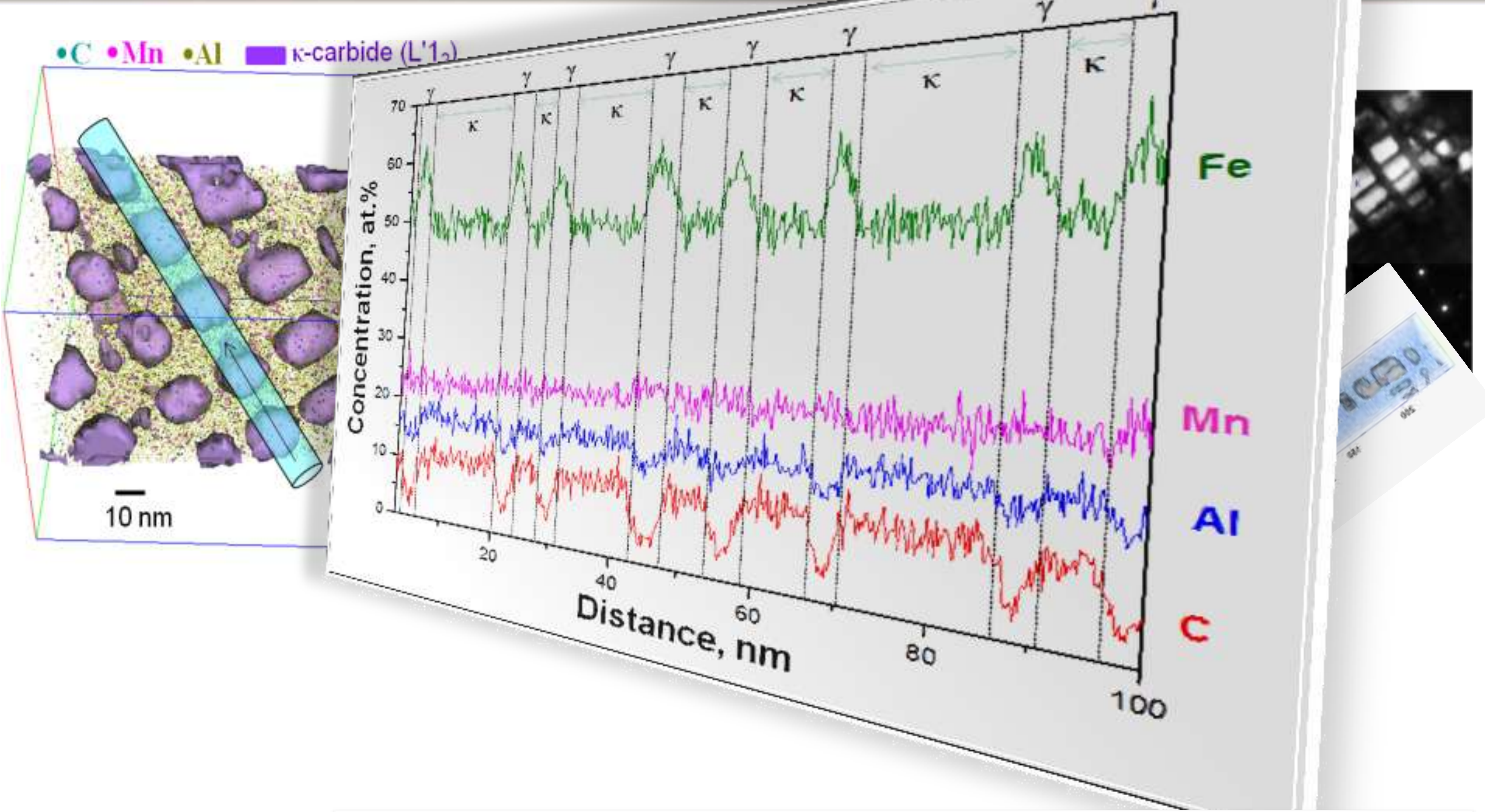




→ lecture by Springer

→ poster by Gutierrez

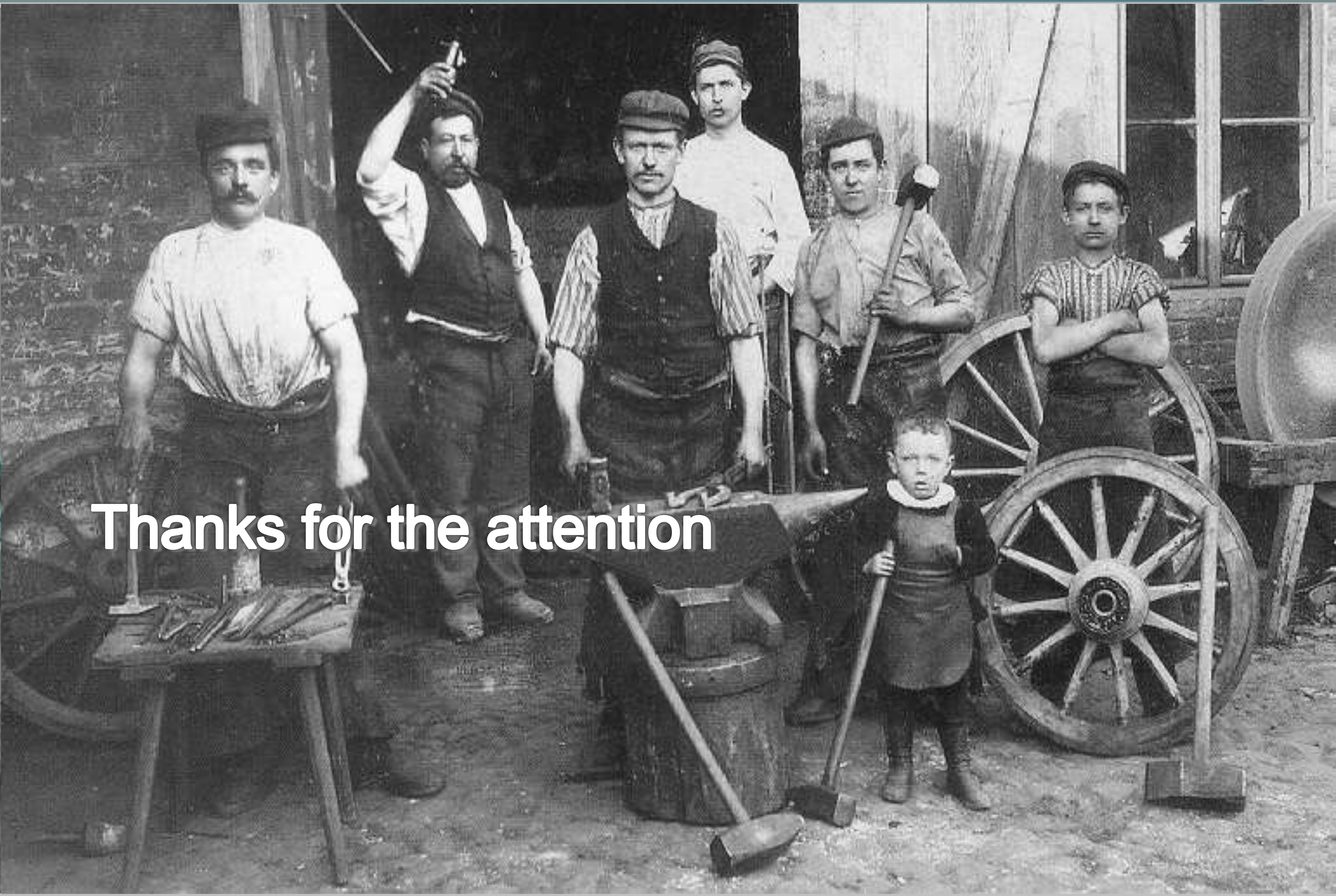
Fe-Mn-Al-C weight reduced alloys (10% less mass density)



- Fe-Mn-Al-C alloys with k-carbides: 1.5 GPa, 80% ductility
- Thermal stability
- Deformation mechanisms depend on local composition

Conclusions

- Design alloys by self-organized nanostructuring
- Segregation plus confined phase transformation at defects
- Works for dislocations too?
- Deformation-driven mechanical bulk alloying leads to non-equilibrium phases approaching the theoretical limits of strength
- Designing stable nanocarbides enables weight-reduced ultra-ductile and thermally stable materials


Thanks for the attention