Alloy design of nanoprecipitate-hardened high-Mn maraging-TRIP and -TWIP steels

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- **Introduction**
- Compositions and processing
- Mechanical properties and microstructures
- Characterization of precipitations
- Formation of new austenite during aging
- Conclusions

Steel for automotive applications:

Good combination of **strength**, **ductility**, **price**

Lean Maraging TRIP Steels

- **Ductile low carbon martensite matrix**
- **Small amount of austenite (TRIP, TWIP)**
- **Controlled precipitation hardening**

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Compositions in mass%: classical maraging steel

Steel	C	Ni	Co	Mo	Ti	Al	Mn	Fe
Maraging	0.01	18	12	4	1.6	0.15	0.05	Balance

Low carbon: ductile martensite

Precipitation hardening

Expensive for automotive applications !

Optimised for very high strength + toughness

We want high strength + ductility

Compositions in mass%: new lean maraging steels

Steel	C	Ni	Co	Mo	Ti	Al	Mn	Fe
Maraging	0.01	18	12	4	1.6	0.15	0.05	Balance
09MnPH	0.01	2	-	1	1.0	0.15	9	Balance
12MnPH	0.01	2	-	1	1.0	0.15	12	Balance
15MnPH	0.01	2	-	1	1.0	0.15	15	Balance

Low carbon: ductile martensite

Precipitation Hardenable

Mn (+Ni): austenite (TRIP)

Processing

Vacuum induction melting

Annealing

Hot deformation

Solution heat treatment

Quenching ⇨ Martensite + retained austenite

Aging (450°C) "Maraging" retained + new austenite

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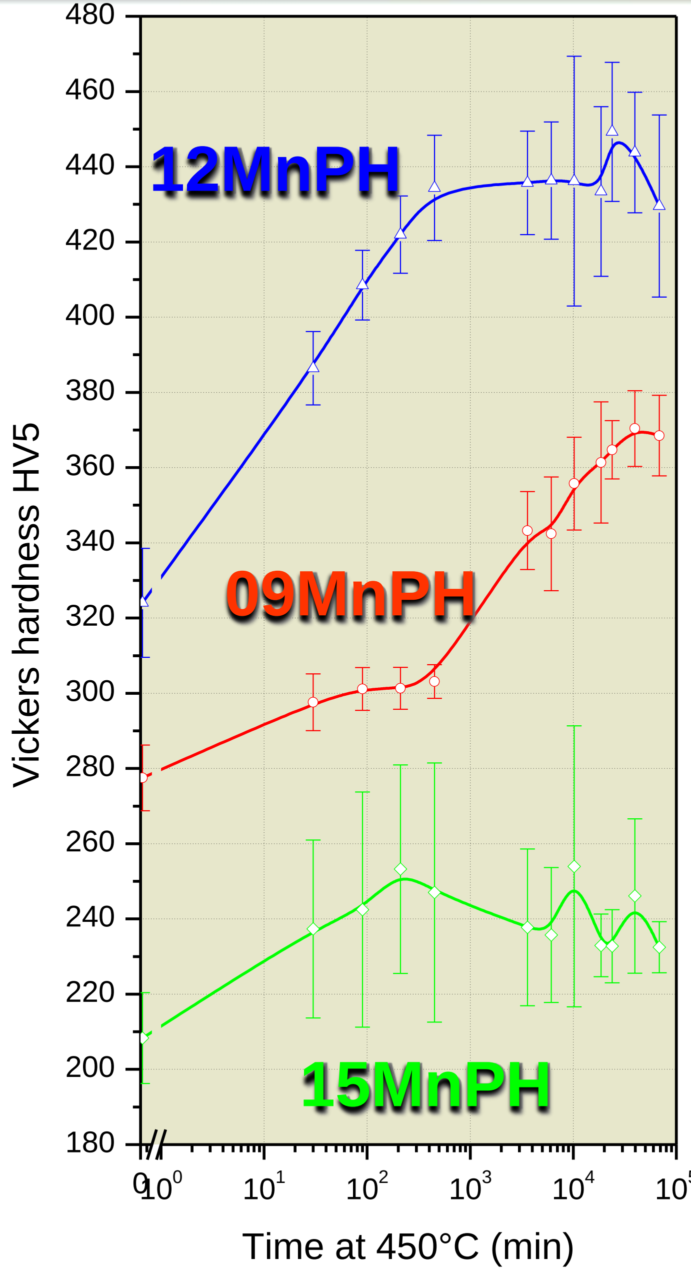
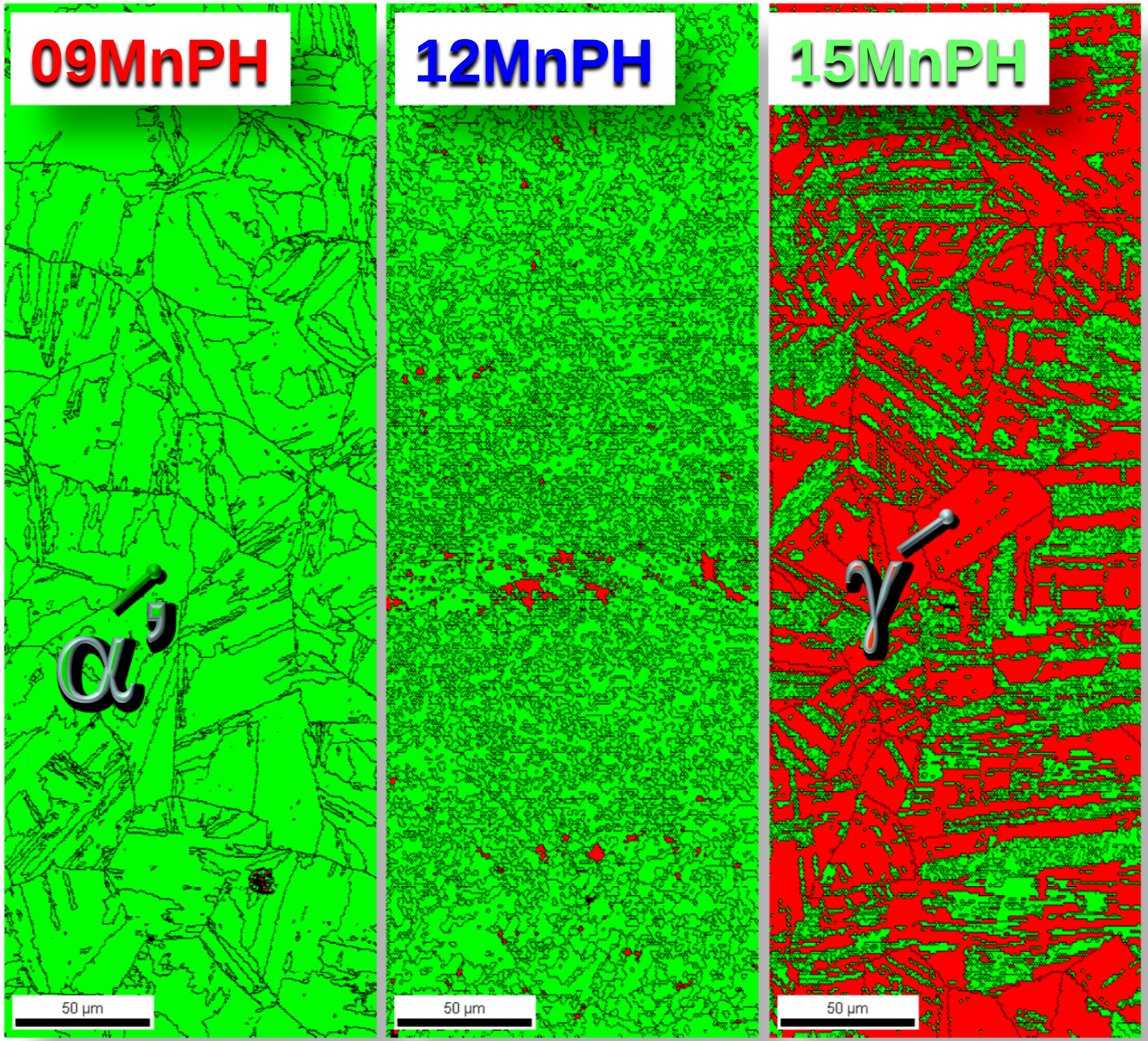
Hardness during aging at 450°C





Phase	Fraction
Iron - Alpha	0.999
Iron - Gamma	0.000

Phase	Fraction
Iron - Alpha	0.982
Iron - Gamma	0.017

Phase	Fraction
Iron - Alpha	0.386
Iron - Gamma	0.614

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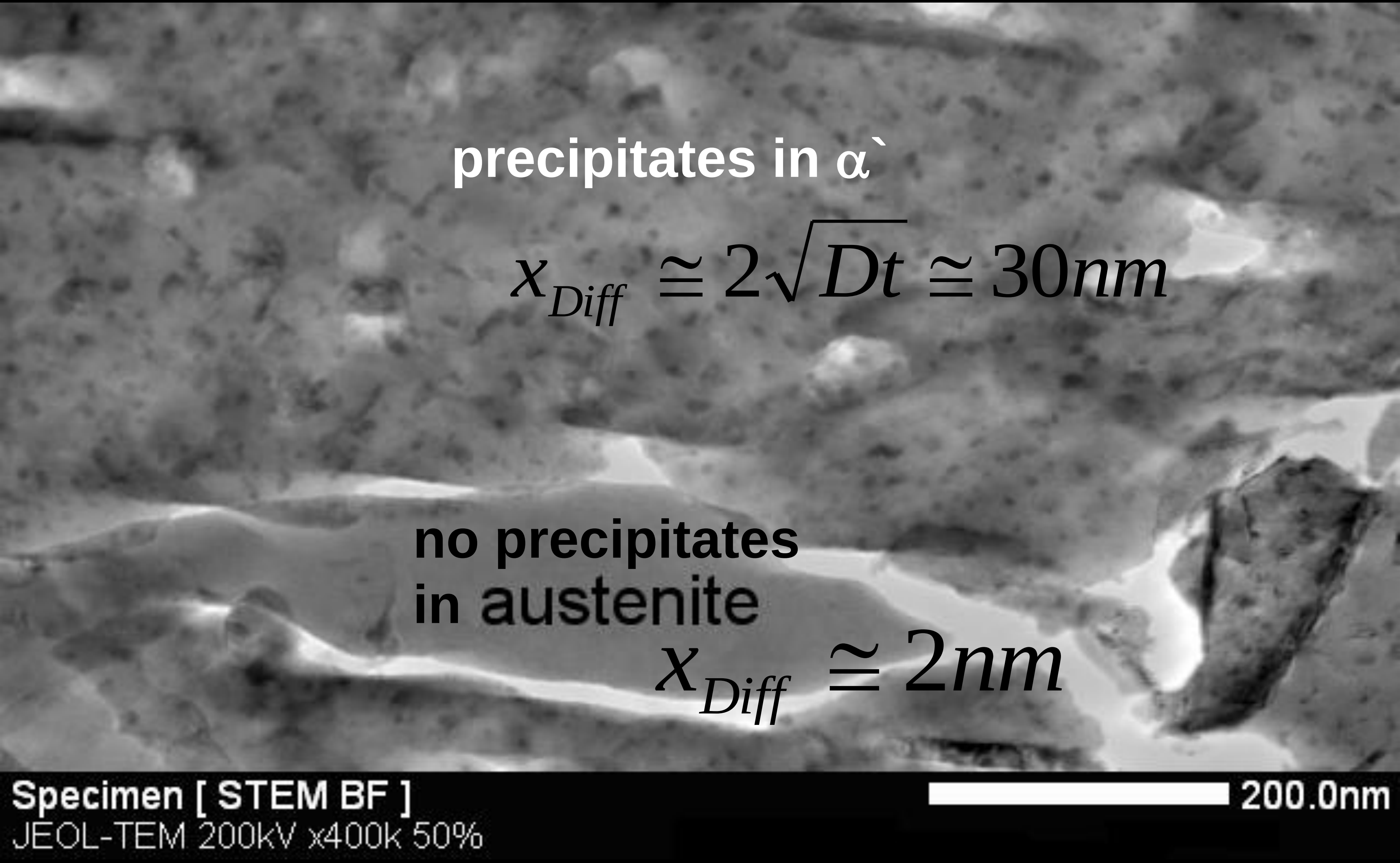
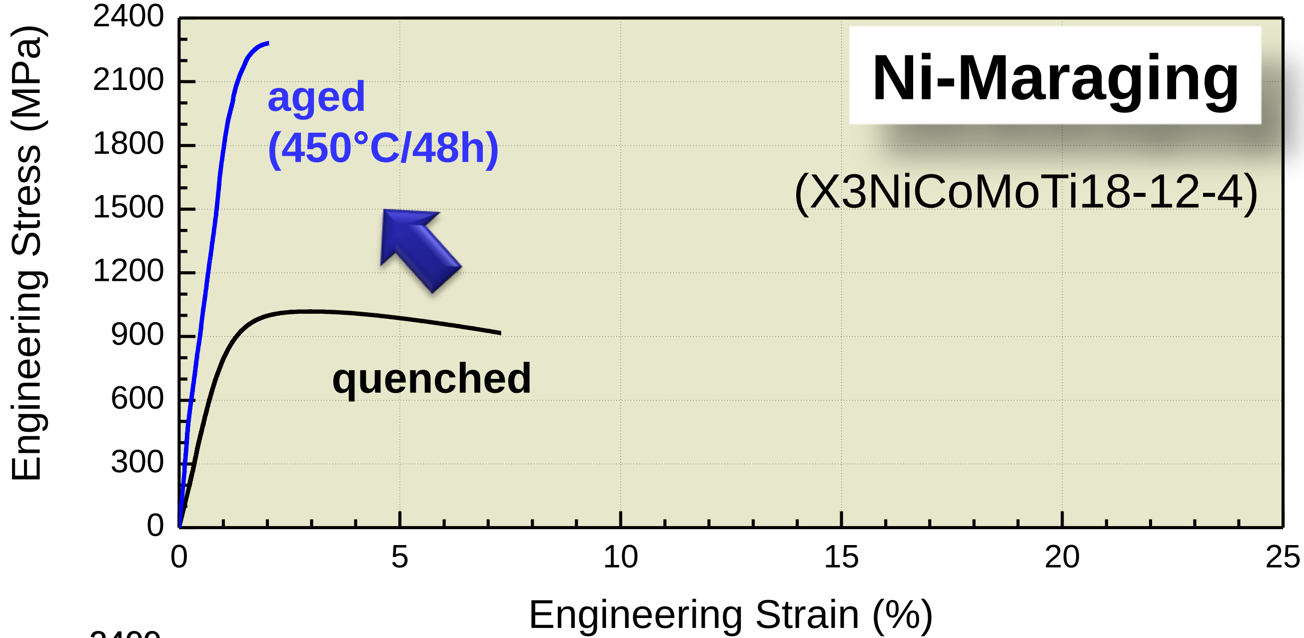
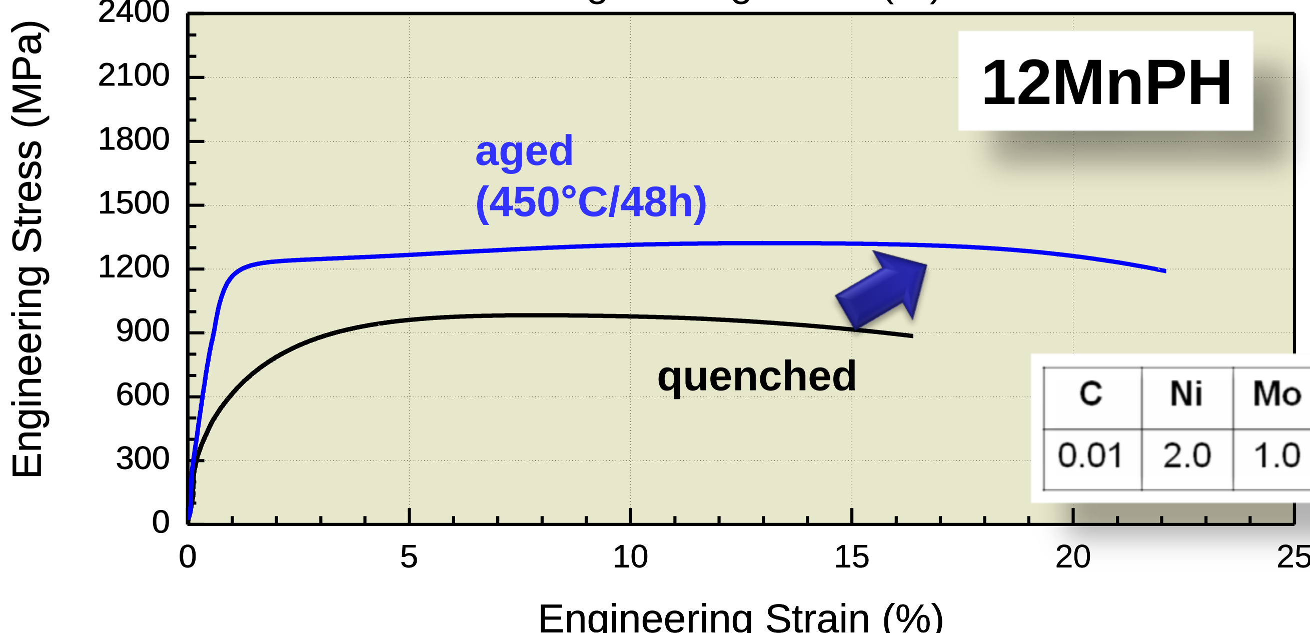
12MnPH after aging (48h 450°C)



Tensile tests





C	Ni	Mo	Ti	Al	Mn	Fe
0.01	2.0	1.0	1.0	0.15	12	bal.

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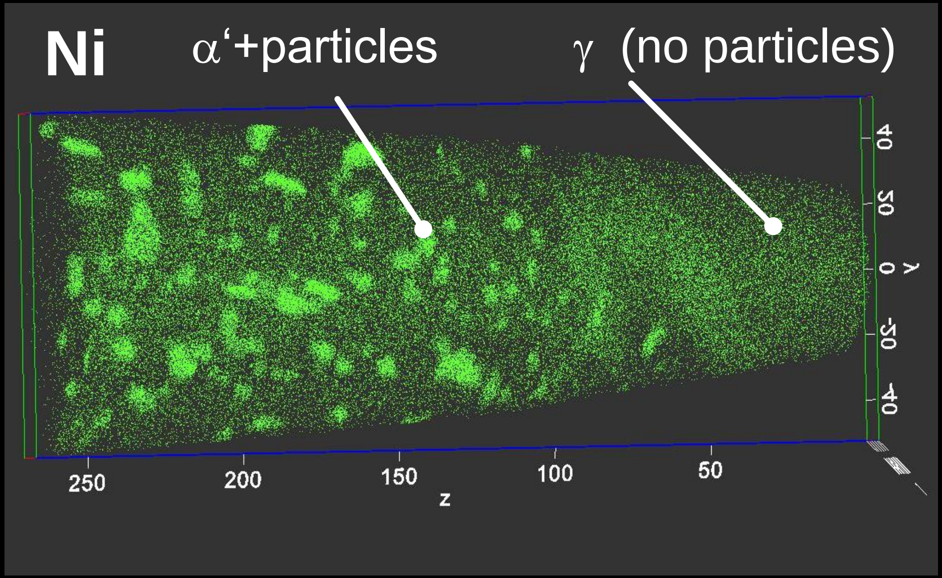
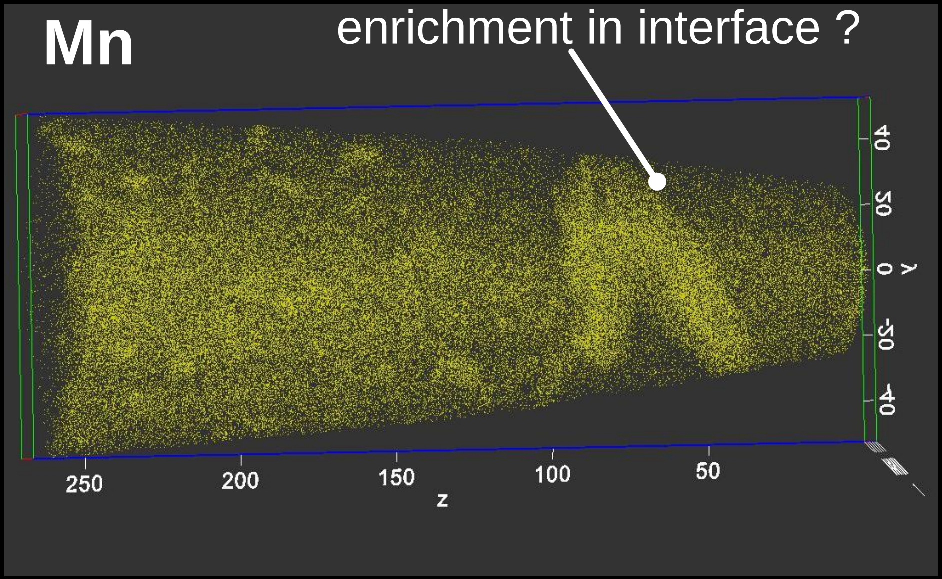
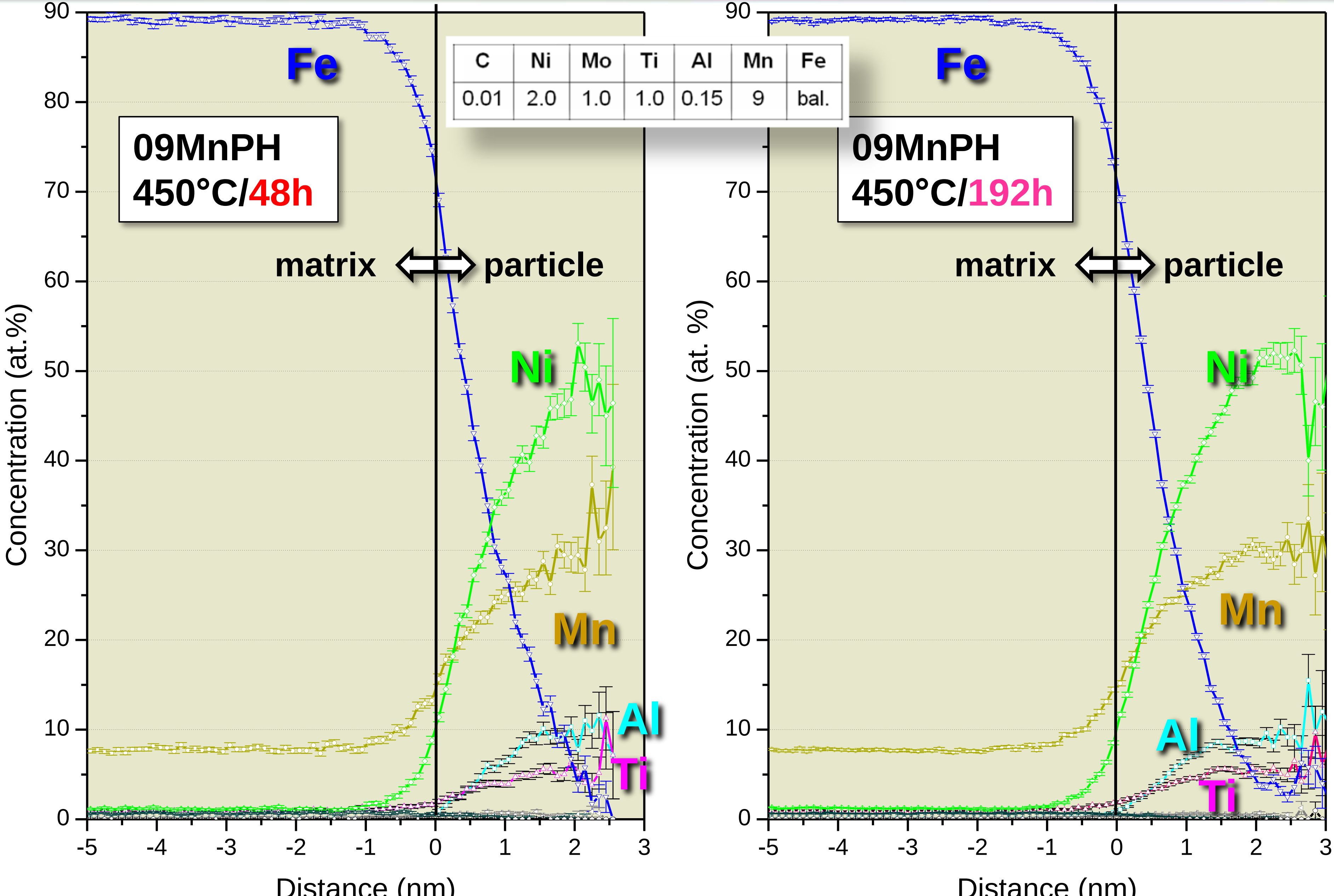
Atom Probe, 12MnPH aged (48h, 450°C)





09MnPH aging at 450°C, Proxigrams

C	Ni	Mo	Ti	Al	Mn	Fe
0.01	2.0	1.0	1.0	0.15	9	bal.



Chemical compositions (09MnPH; 450°C/48h)

	at. % in particles	at. % in particles
Ni	39.99	52.88
Mn	24.70	32.66
Al	7.02	9.28
Ti	3.91	5.17
Fe	23.97	0

Mn + Al + Ti (second column): 47.11

possible: $Ni_{50}(Mn,Al,Ti)_{50}$

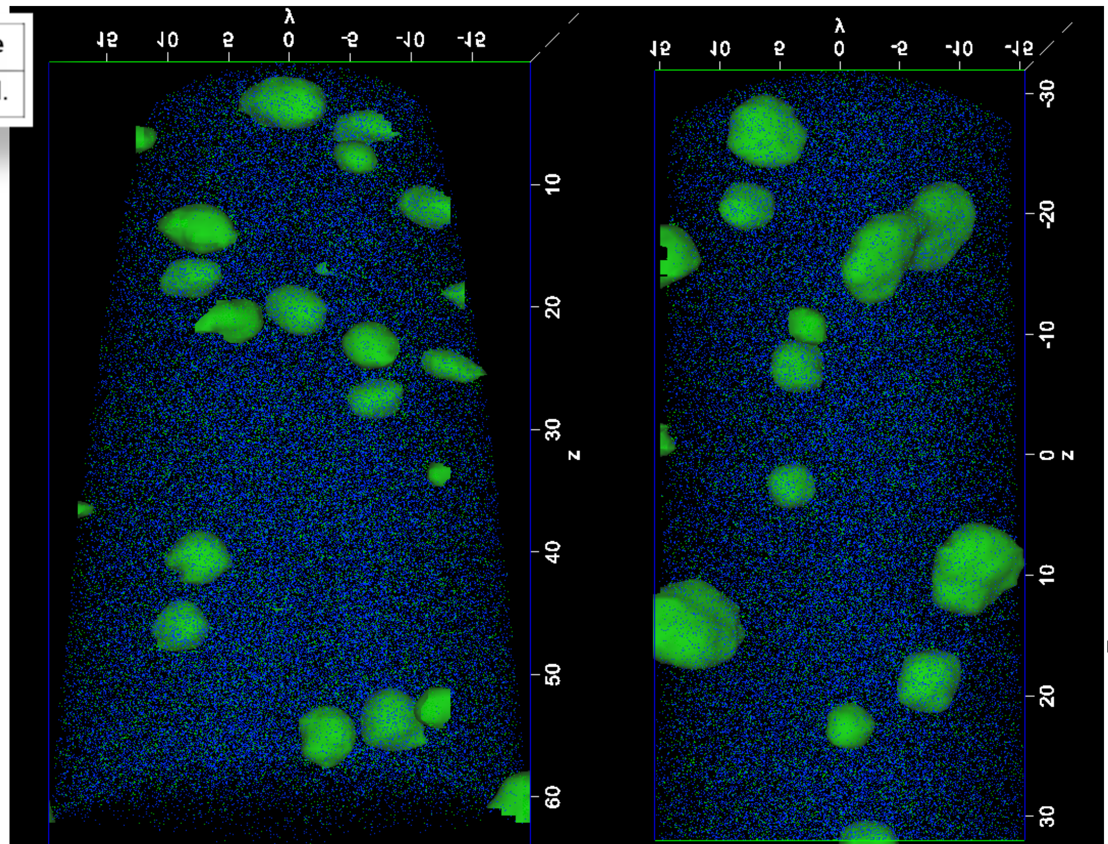
C	Ni	Mo	Ti	Al	Mn	Fe
0.01	2.0	1.0	1.0	0.15	9	bal.

09MnPH aging at 450°C

Aging time at 450°C	48 hours	192 hours
Volume fraction of particles	1.5%	4.3%
Number density of particles (m^{-3})	3.6×10^{24}	1.9×10^{24}
Mean diameter (nm)	4.7 ± 0.7	6.1 ± 2.2

C	Ni	Mo	Ti	Al	Mn	Fe
0.01	2.0	1.0	1.0	0.15	9	bal.

48 hours



192 hours

10 nm

Iso-conc. surfaces:
14 at.% Ni

only **Fe** and **Ni** shown

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- After aging (48h 450°C) nanosized precipitations in martensite
  (Ø ~ 5nm; volume fraction ~ 1.5%)

- Heusler Alloy (**Ni_2MnAl**)? B2 or $L2_1$? Coherent ?
  Cut by dislocations ?

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Effect of aging on ductility

12MnPH

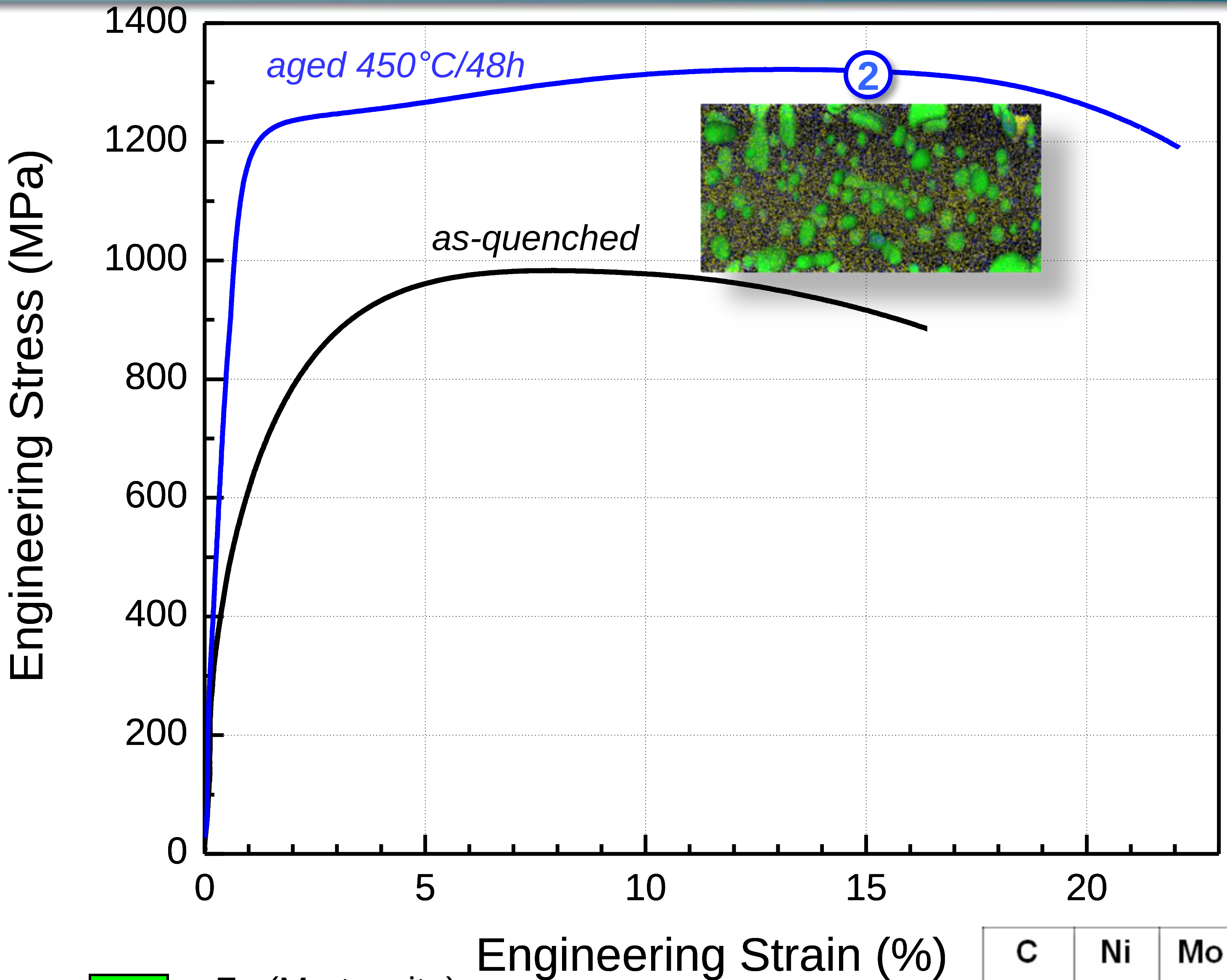
12 wt.% Mn, 0.01 wt.% C, **2 wt.% Ni**, **1 wt.% Ti**, **0.15 wt.% Al**, 1 wt.% Mo, 0.06 wt.% Si

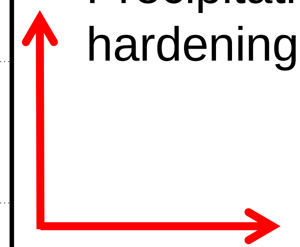
TRIP effect
(austenite
transforms to martensite)

Maraging effect
(precipitation hardening
in martensite)

D. Raabe, D. Ponge, O. Dmitrieva, B. Sander, Scripta Mater. 60 (2009) 1141
D. Raabe, D. Ponge, O. Dmitrieva, B. Sander, Adv. Eng. Mater. 11/7 (2009) 547

Effect of aging on ductility





Precipitation hardening

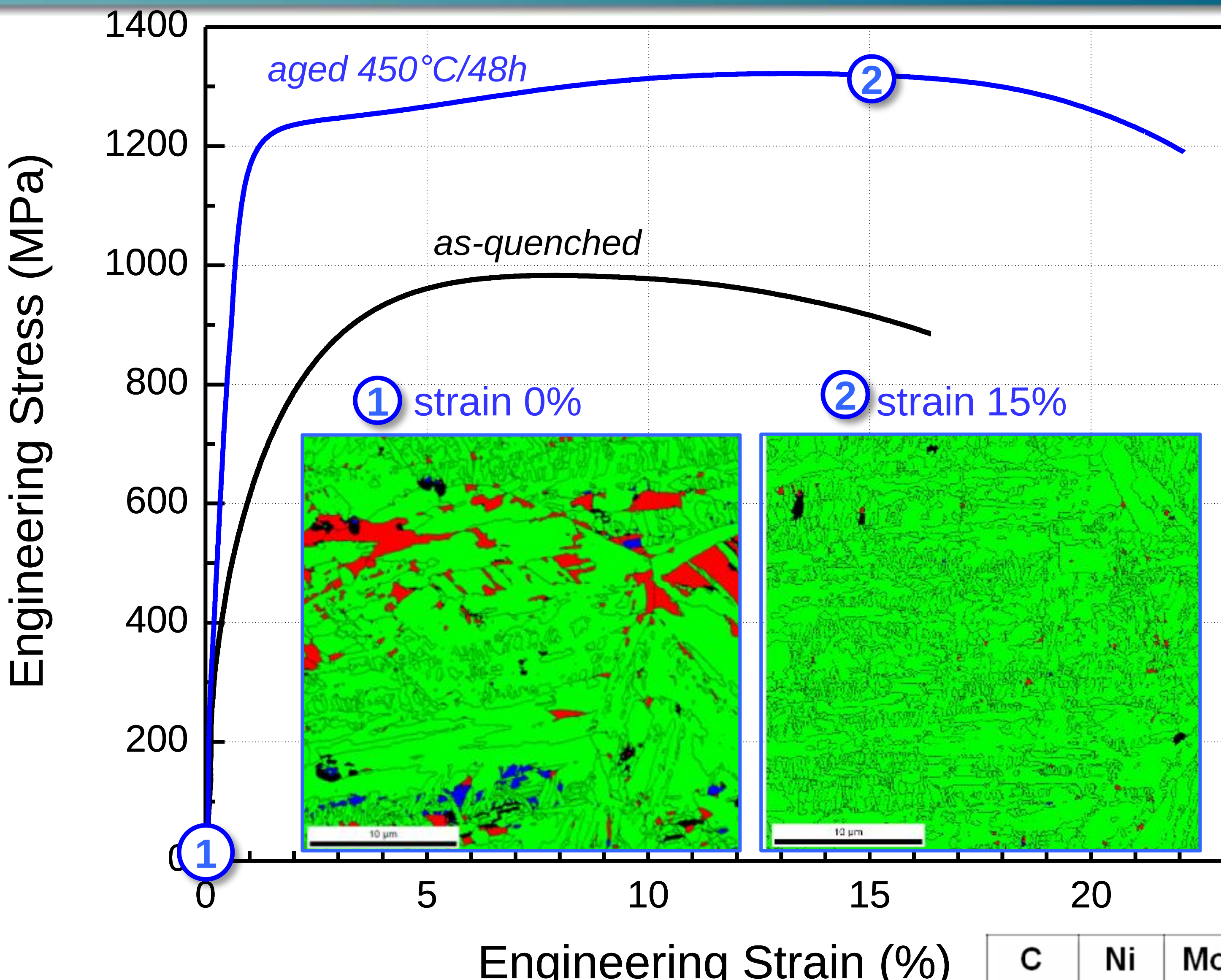
increase of austenite fraction during aging

α-Fe (Martensite)

γ-Fe (Austenite), vol. fraction 15-20%

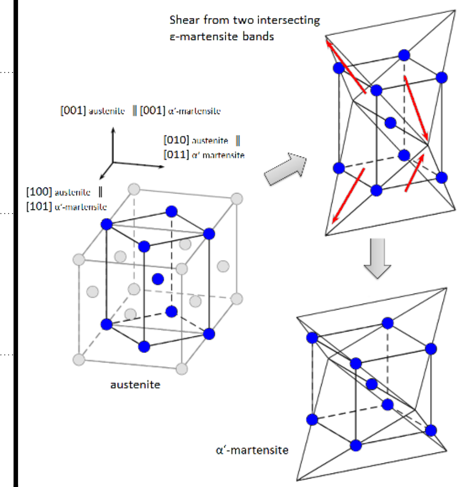
C	Ni	Mo	Ti	Al	Mn	Fe
0.01	2.0	1.0	1.0	0.15	12	bal.

Effect of aging on ductility



Precipitation hardening

increase? of austenite fraction during aging

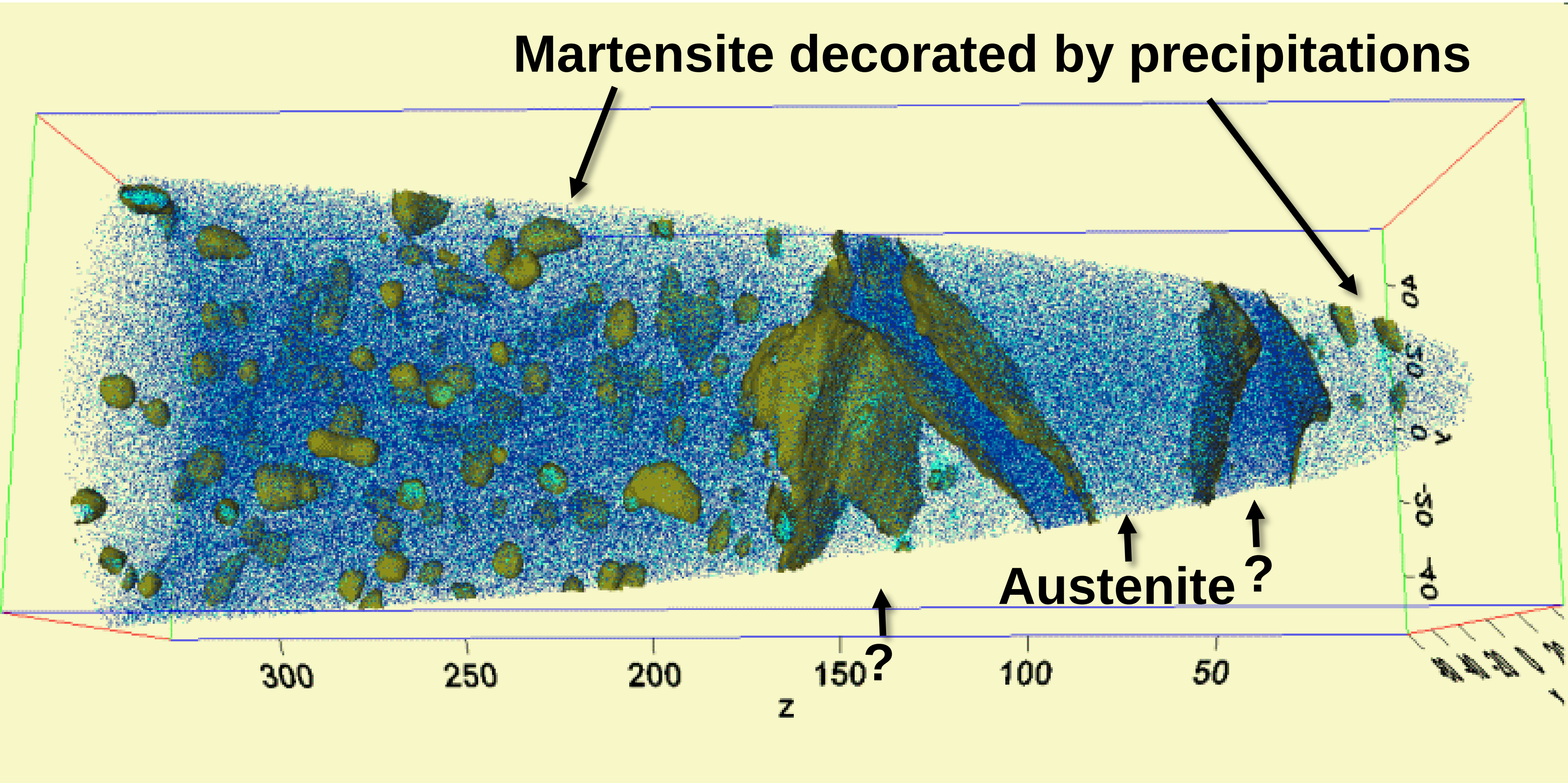


α-Fe (Martensite)

γ-Fe (Austenite), vol. fraction 15-20%

C	Ni	Mo	Ti	Al	Mn	Fe
0.01	2.0	1.0	1.0	0.15	12	bal.

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



Mn atoms, Ni atoms
Mn iso-conc: 18 at.%

C	Ni	Mo	Ti	Al	Mn	Fe
0.01	2.0	1.0	1.0	0.15	12	bal.

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

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Conclusions

Design of "Lean Maraging TRIP steel"

Precipitation hardening ⇨ Increase strength

Austenite (retained + new) ⇨ Increase ductility

- Martensitic Mn-steels (~0,01wt%C): good ductility
- + controlled amounts of Ni (2 wt%), Al (0.15 wt%), … increase strength during aging by formation of nanosized precipitations without significant reduction of ductility
- By controlling the austenite stability (here by Mn) martensite can be refined and ductility can be further increased by retained and reverted austenite (TRIP)