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

D. Ponge, O. Dmitrieva, J. Millán, S. Sandlöbes, P. Choi,
A. Kostka, G. Inden, D. Raabe

Max-Planck-Institut
für Eisenforschung GmbH
Düsseldorf, Germany
WWW.MPIE.DE
d.raabe@mpie.de

The 1st International Conference on **H**igh **M**anga**n**ese **S**teels 2011
Hilton Hotel Seoul, Korea, May 15-18, 2011

Overview

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

Introduction

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**

Overview

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

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)

Raabe, Ponge, Dmitrieva, Sander: Adv. Eng. Mat. 11 (2009) 547

Processing

Vacuum induction melting

Annealing

Hot deformation

Solution heat treatment

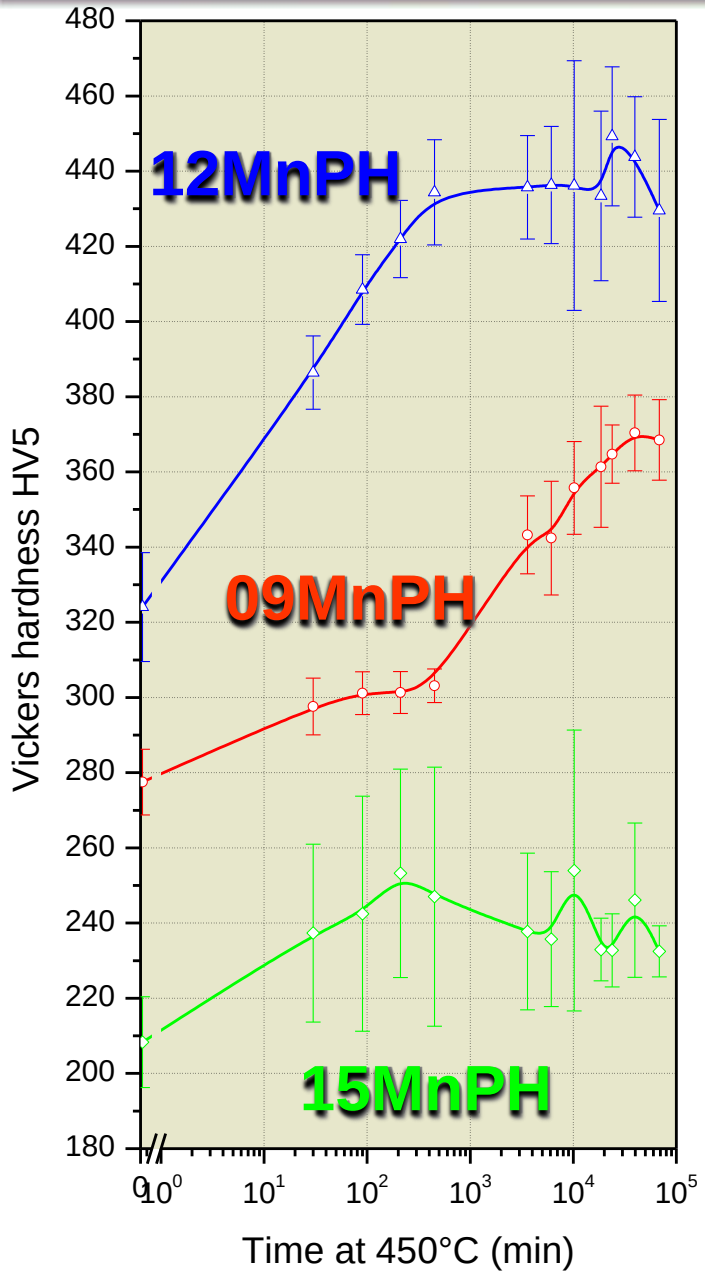
Quenching ⇨ Martensite + retained austenite

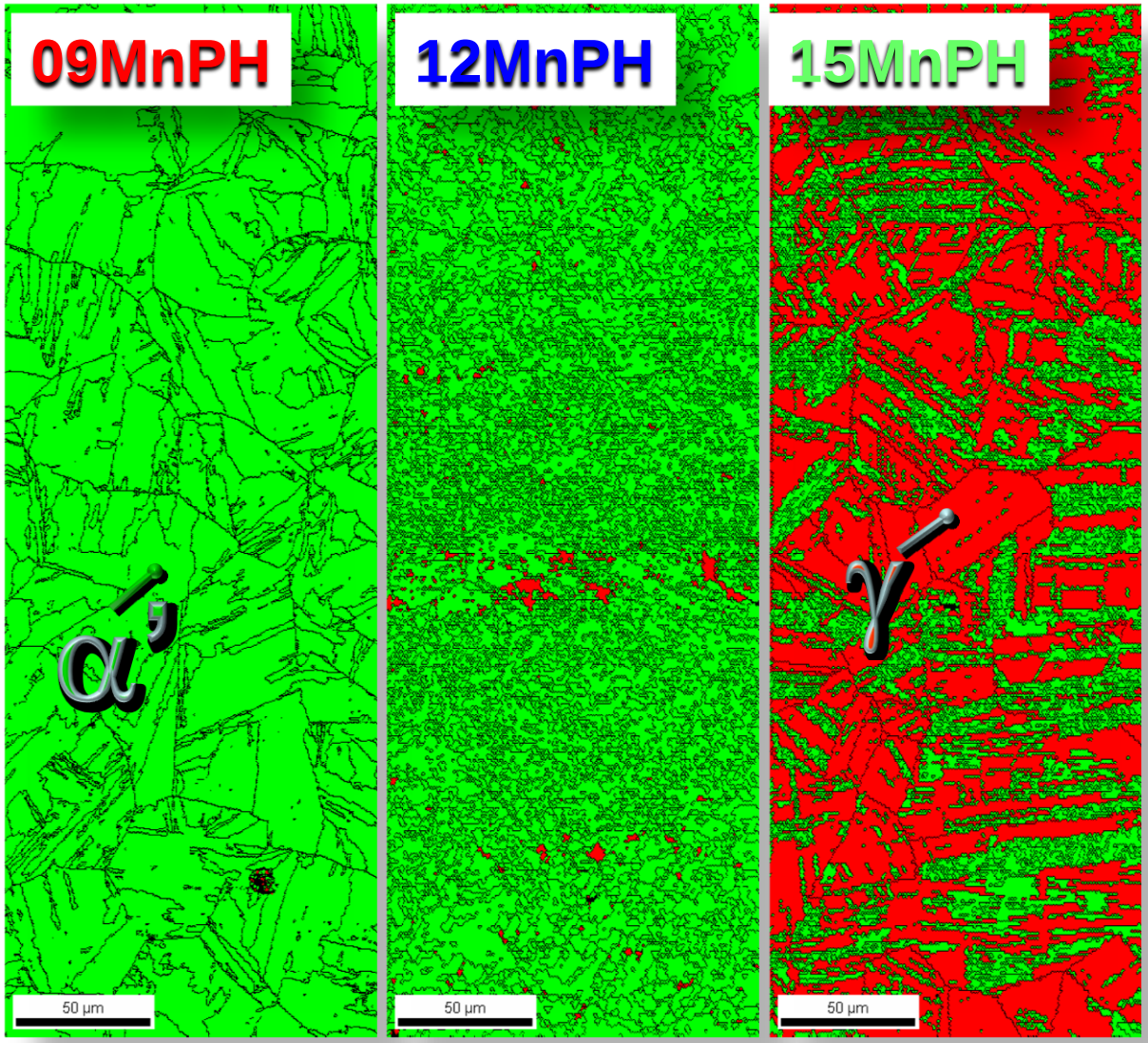
Aging (450°C) "Maraging" retained + new austenite

Overview

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

Hardness during aging at 450°C





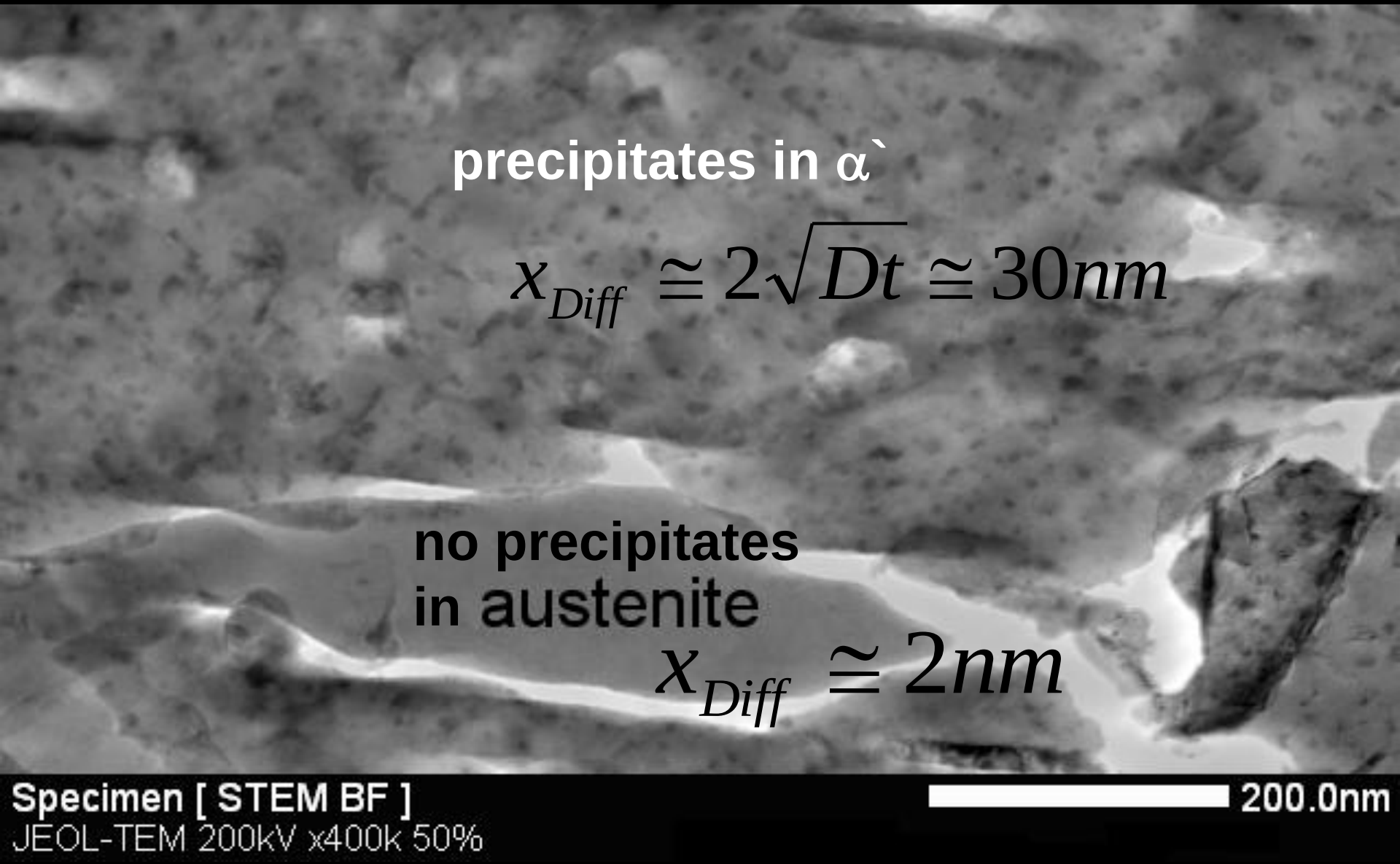
Phase	Fraction
Iron - Alpha	0.999
Iron - Gamma	0.000

Phase	Fraction
Iron - Alpha	0.982
Iron - Gamma	0.017

Phase	Fraction
Iron - Alpha	0.386
Iron - Gamma	0.614

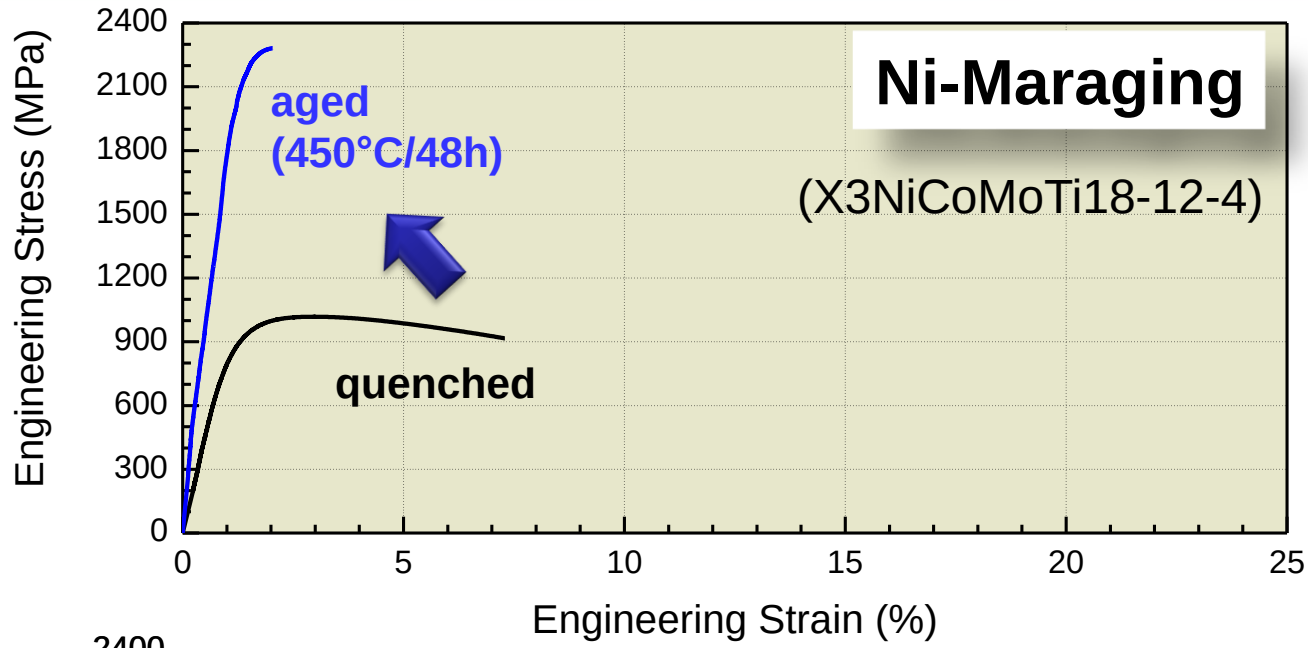
Dmitrieva et al. Acta Mater 59 (2011)

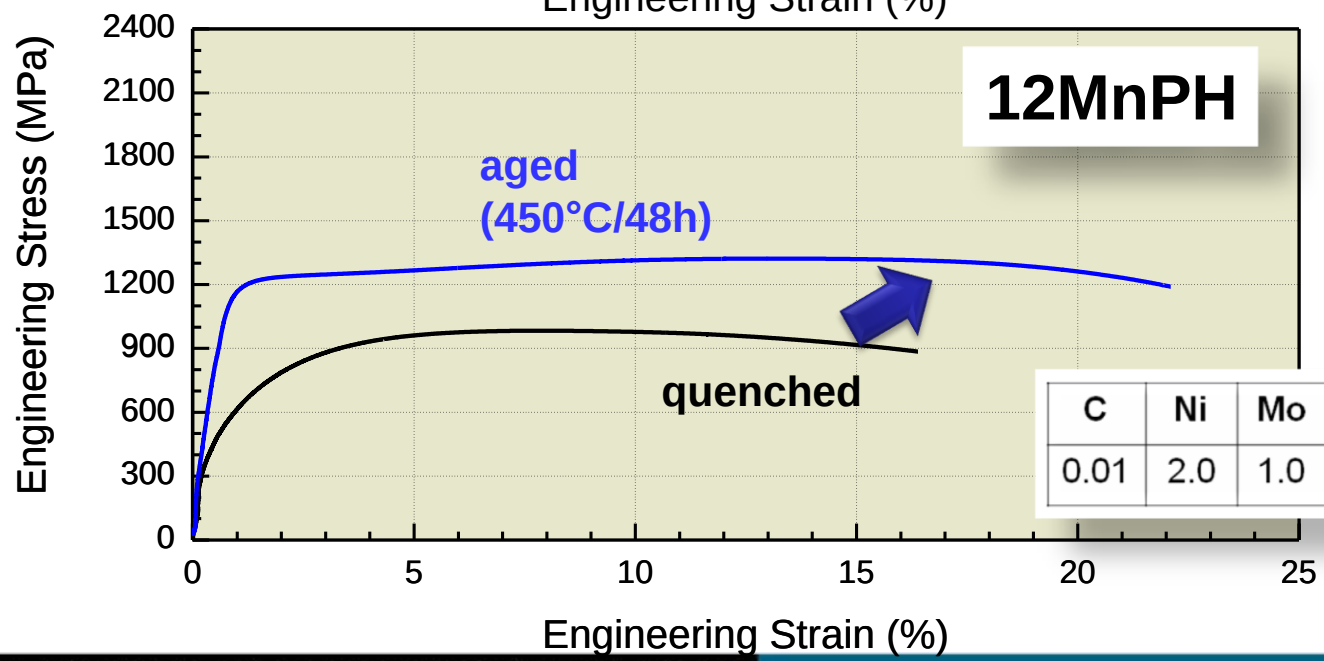
12MnPH after aging (48h 450°C)



Dmitrieva et al. Acta Mater 59 (2011)

Tensile tests





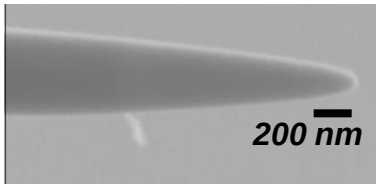
C	Ni	Mo	Ti	Al	Mn	Fe
0.01	2.0	1.0	1.0	0.15	12	bal.

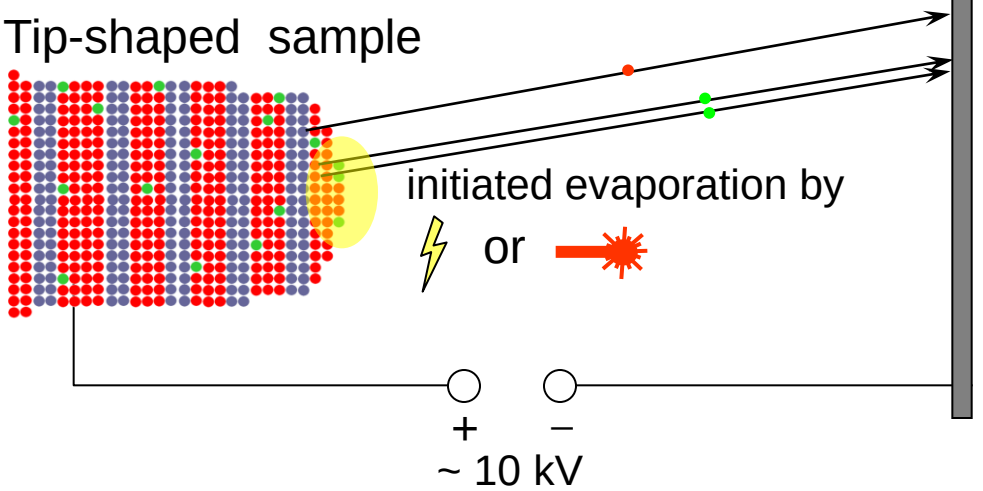
D. Raabe et al. Scripta Materialia 60 (2009) 1141

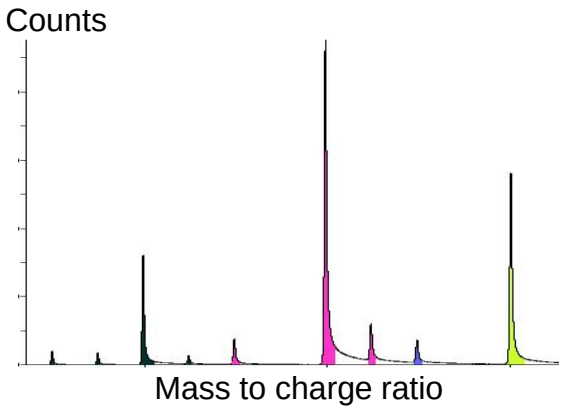
Overview

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

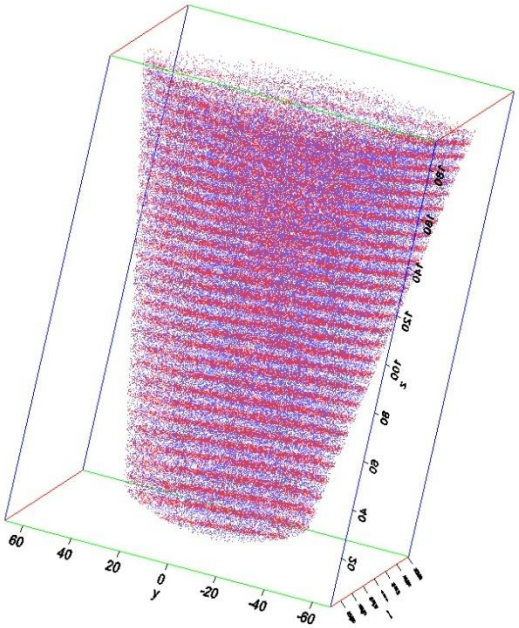
Atom Probe Tomography (APT)





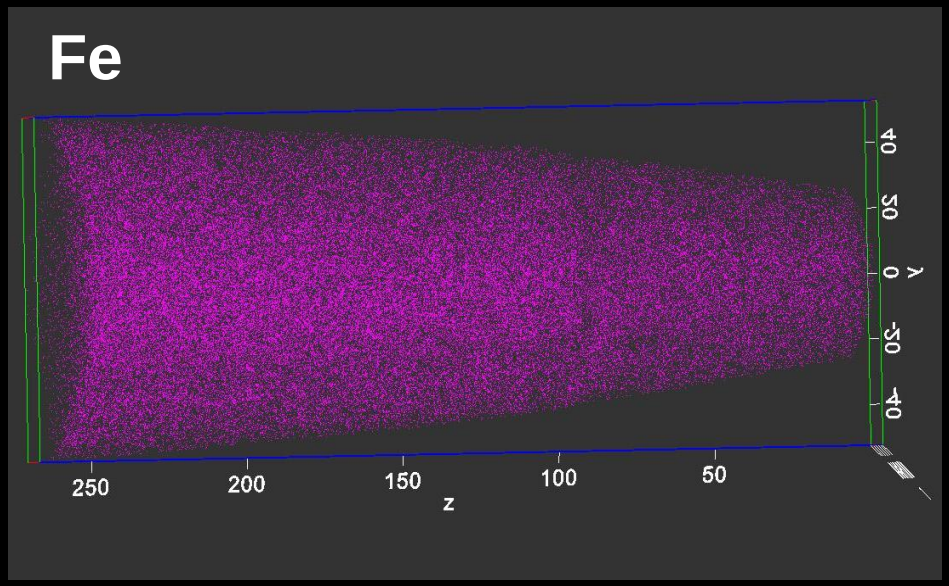


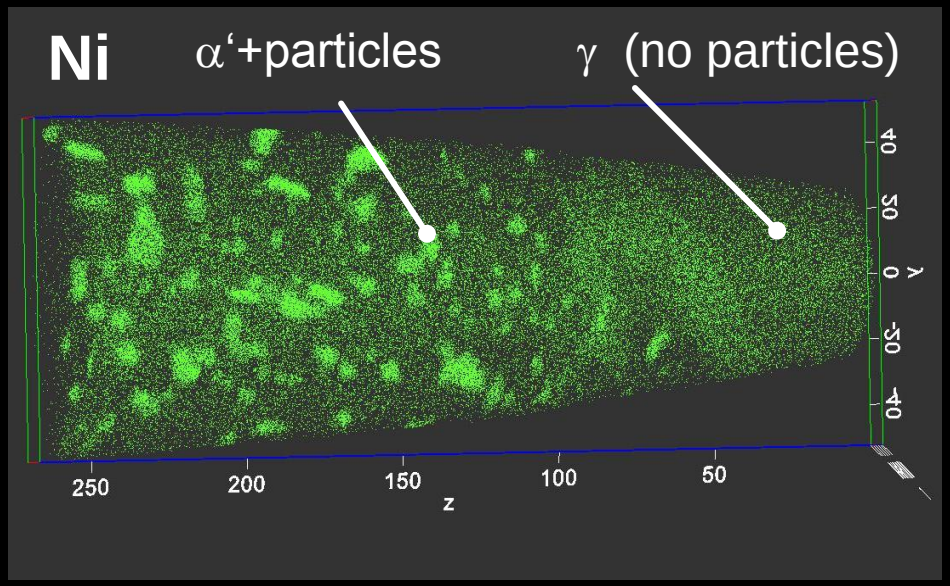
3D atom map

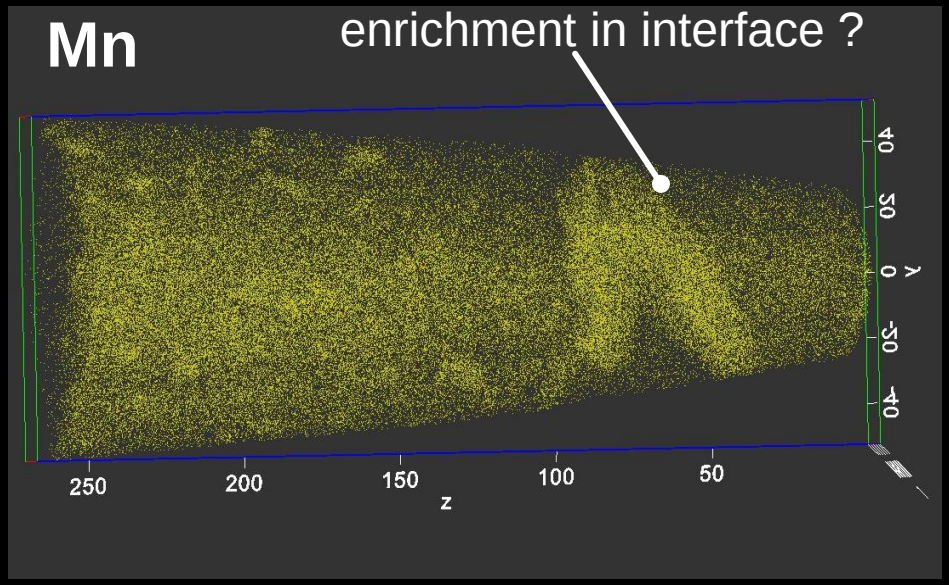


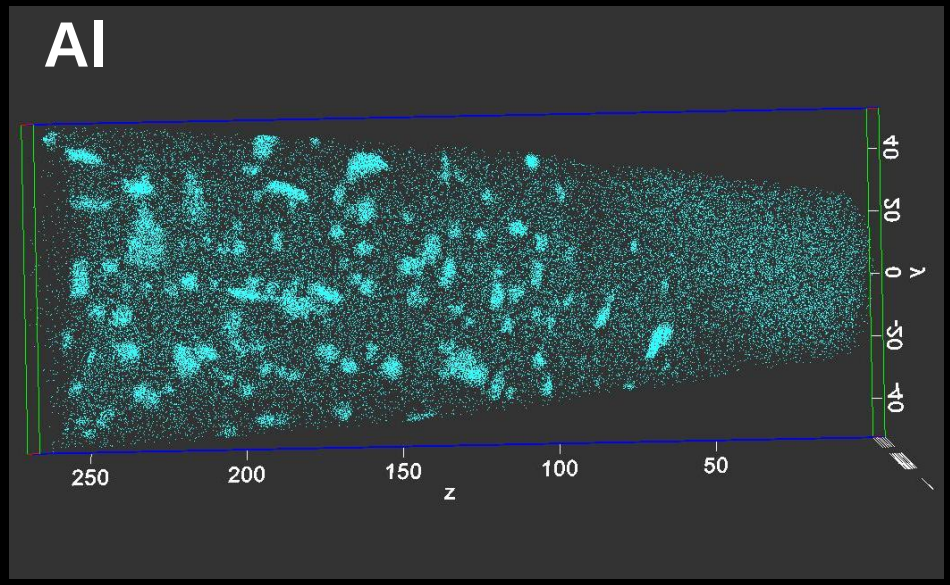
APT: Time of flight measurement
(chemical identification)
+
Ion projection microscopy
(determination of position)

Atom Probe, 12MnPH aged (48h, 450°C)





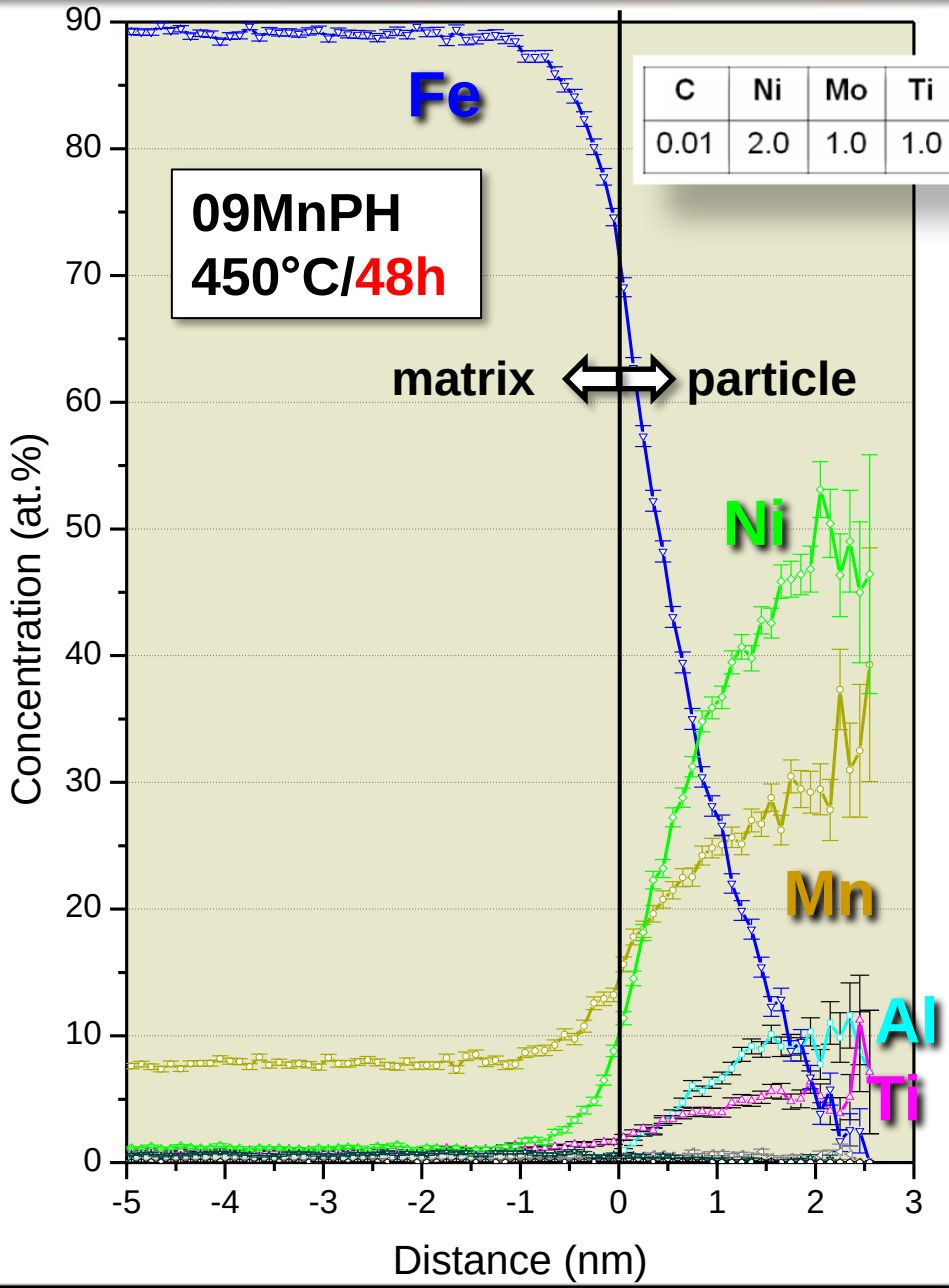


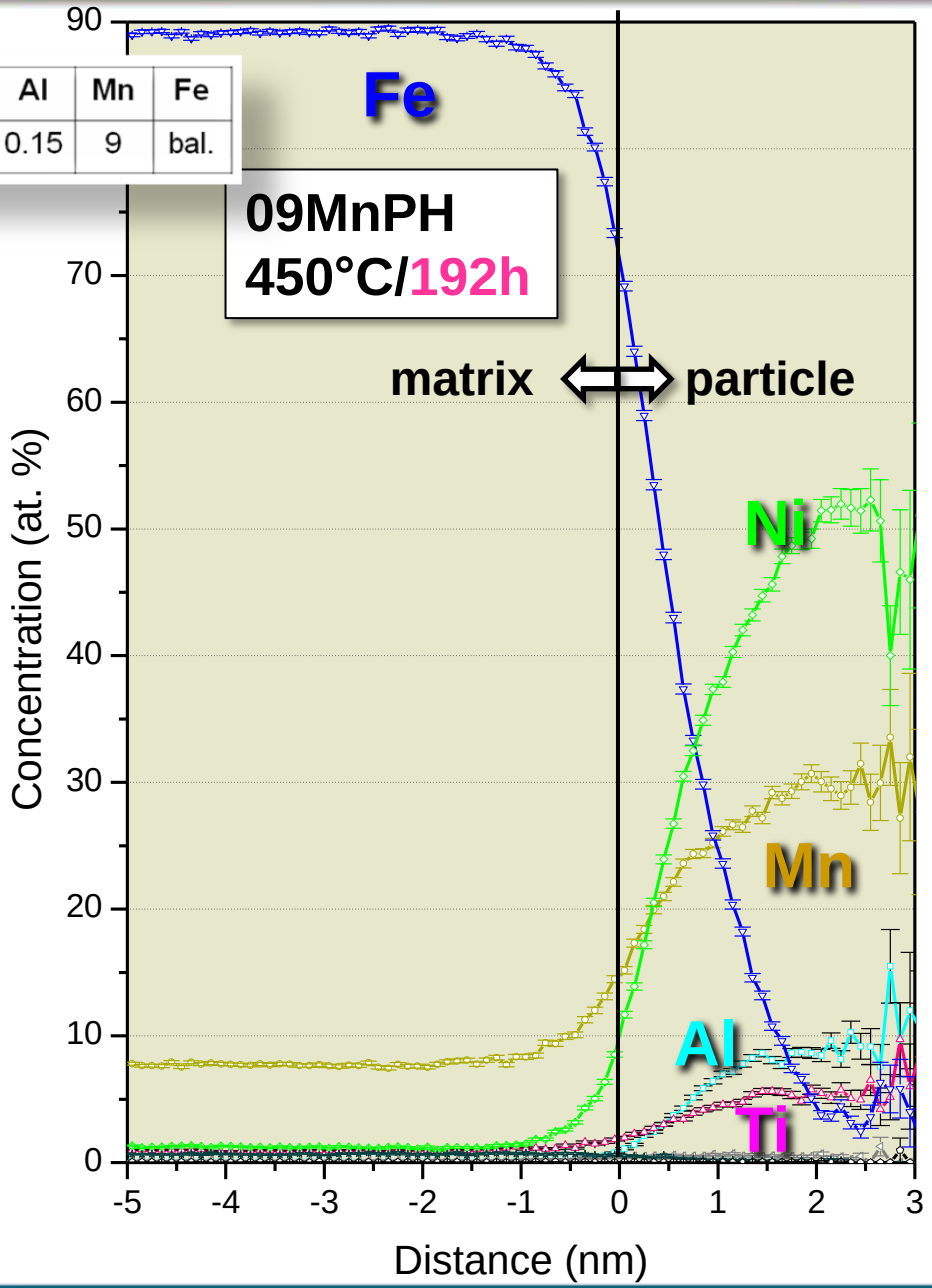


Dmitrieva et al. Acta Mater 59 (2011)

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.





Dmitrieva et al. Acta Mater 59 (2011)

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

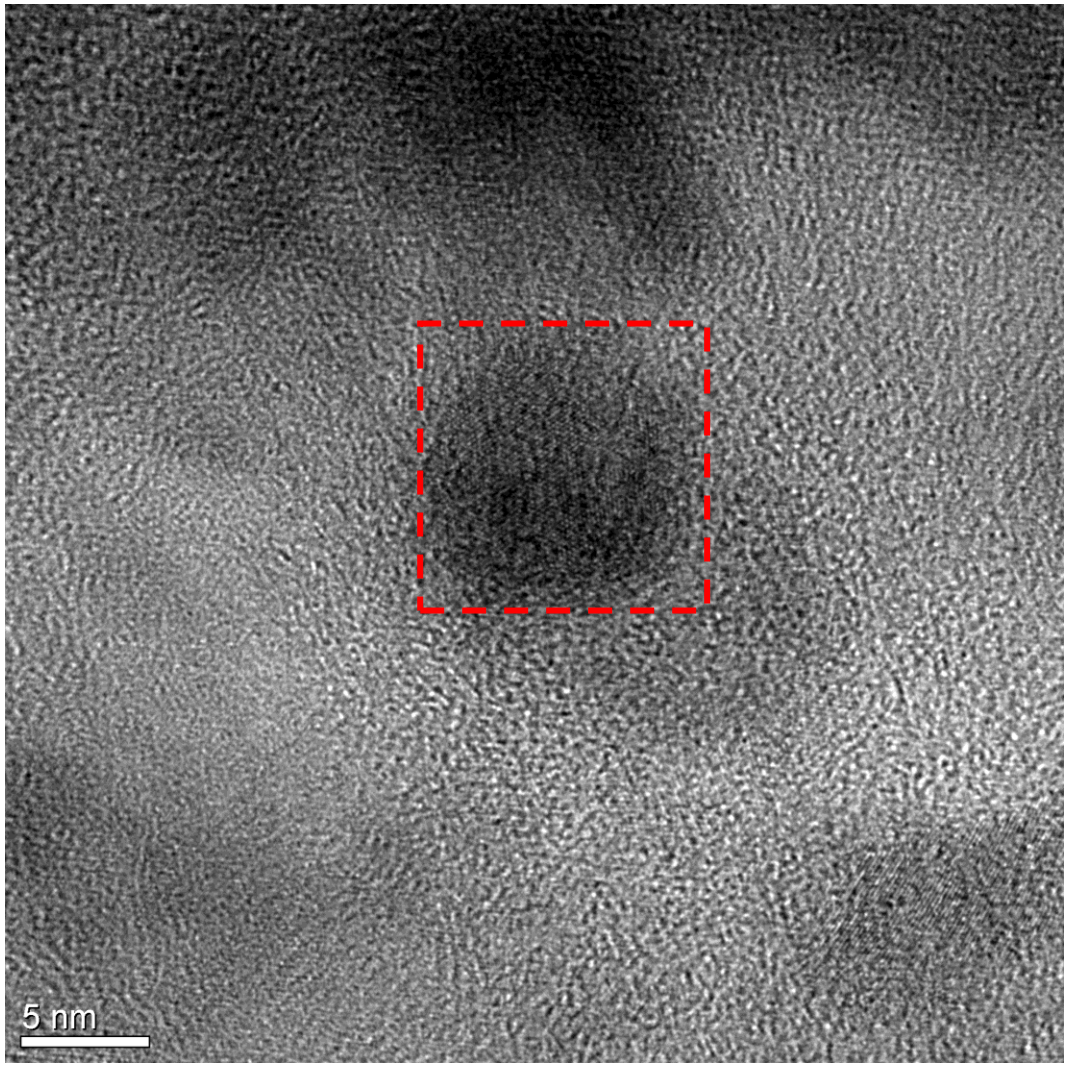
	at. % in particles	at. % in particles
Ni	39.99	52.88
Mn	24.70	32.66
Al	7.02	9.28
Ti	3.91	5.17
Fe	23.97	0

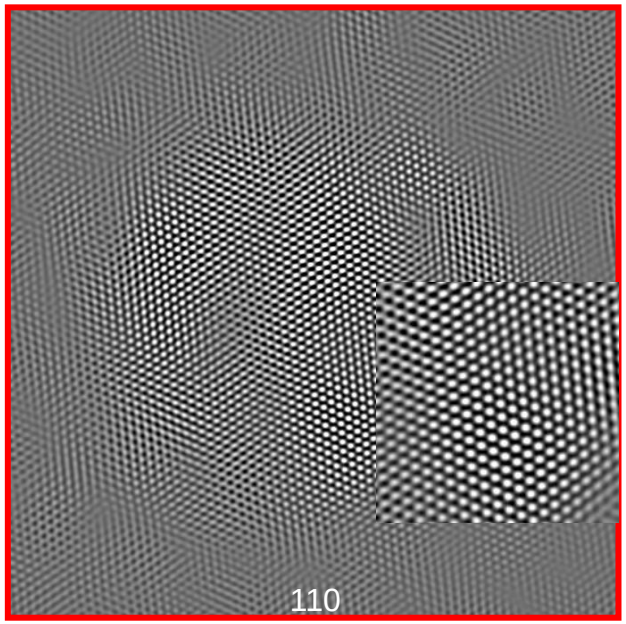
47.11

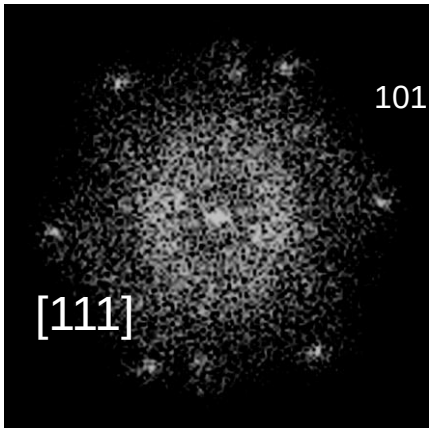
possible: $Ni_{50}(Mn,Al,Ti)_{50}$

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

TEM results (09Mn PH after 192h/450°C)







Particle: a=0.280 ± 0,006nm (assuming bcc structure)

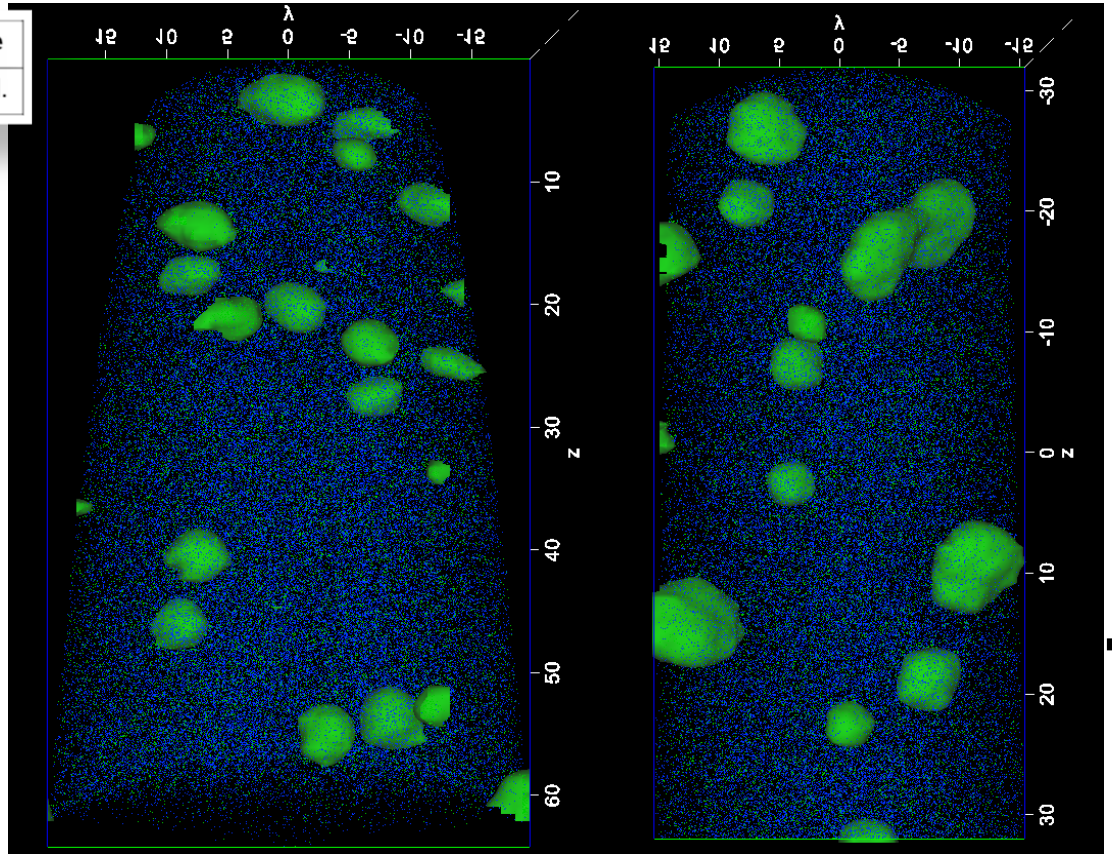
Matrix: a=0.275 ± 0,003nm

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

Dmitrieva et al. Acta Mater 59 (2011)

09MnPH (48h, 450°C)

⇒ Precipitation volume fraction f about 1.5%

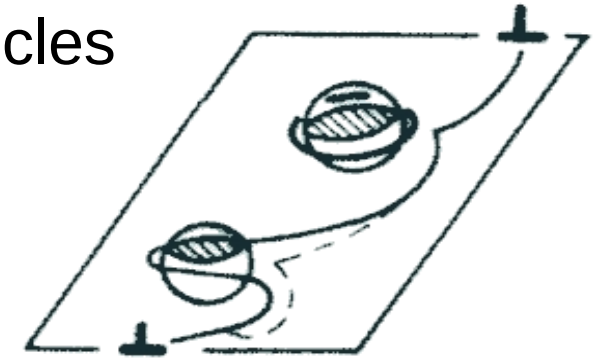
Mean diameter d = 4.7 nm (± 0.7 nm)

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

Assuming dislocations bypassing particles (Orowan looping):

$$\sigma_{OR} \cong \frac{MGb\sqrt{f}}{r}$$

$$\sigma_{OR} \cong \frac{3 \cdot 80GPa \cdot 0{,}248nm\sqrt{0{,}015}}{2{,}35nm} = 3100MPa$$

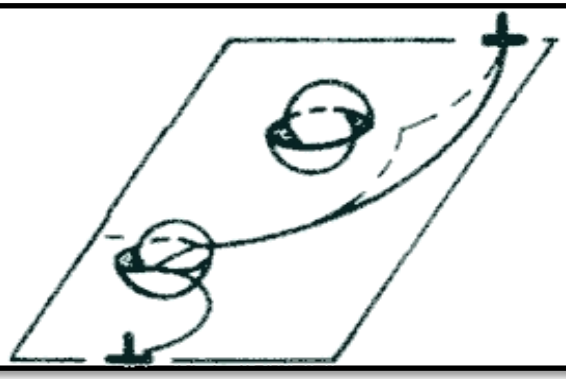


From experiment:

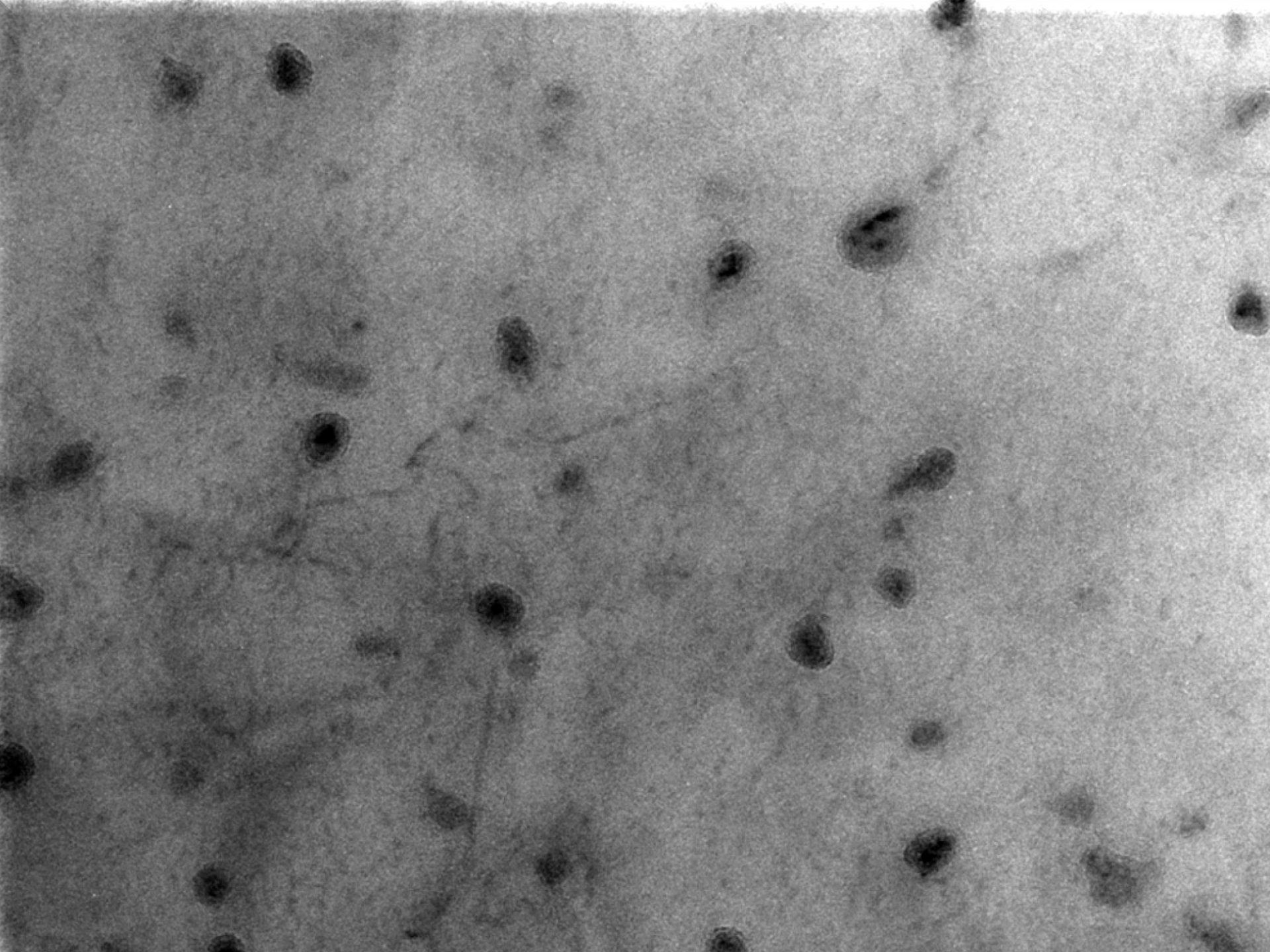
ΔYS: ~300MPa

Shearable coherent particles ?

Cutting of particles (Friedel cutting) ?



Dmitrieva et al. Acta Mater 59 (2011)



Precipitations

- 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 ?

Overview

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

Effect of aging on ductility

12MnPH

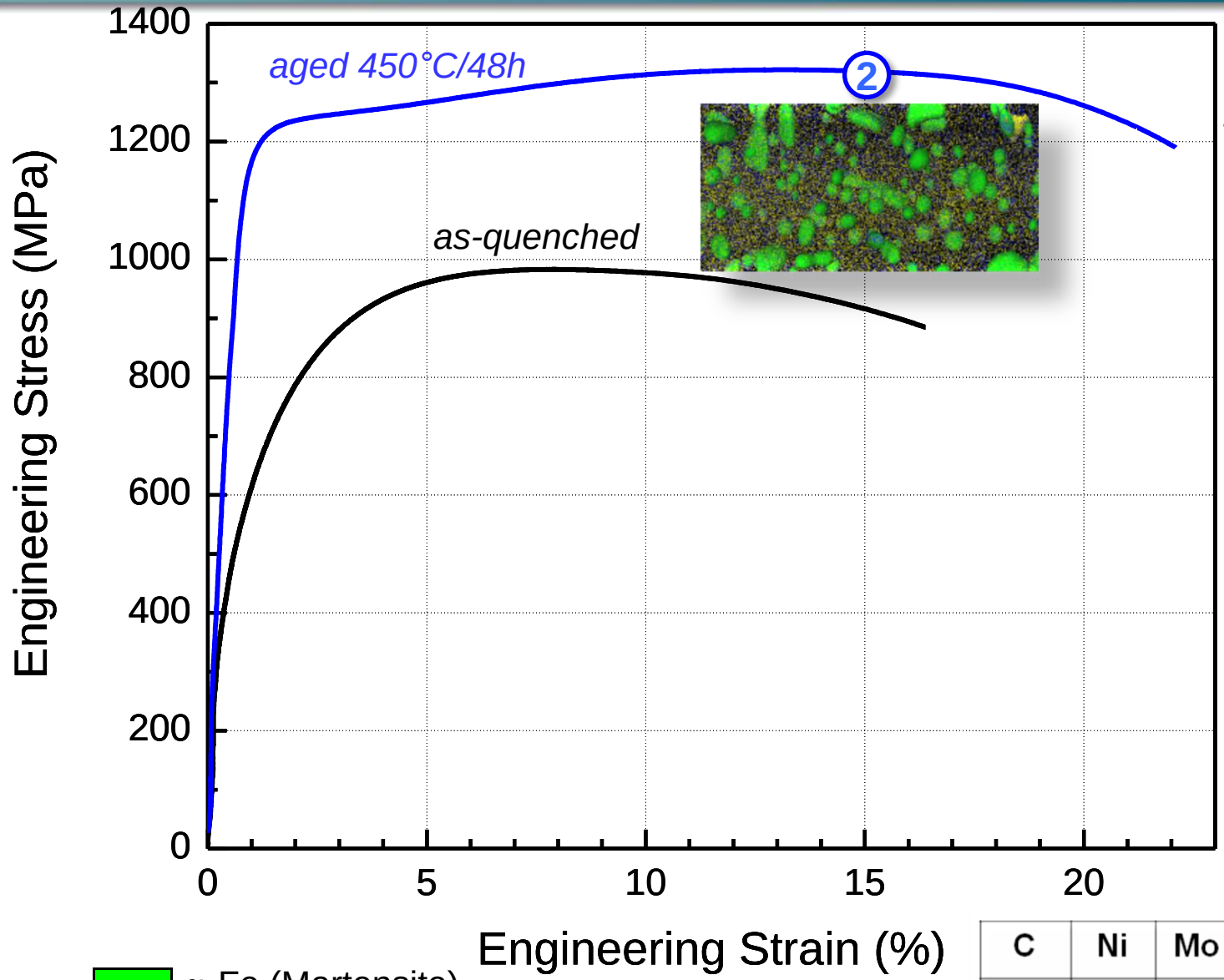
12 wt.% Mn, 0.01 wt.% C, **2 wt.% Ni**, **1 wt.% Ti**, **0.15 wt.% Al**, 1 wt.% Mo, 0.06 wt.% Si

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

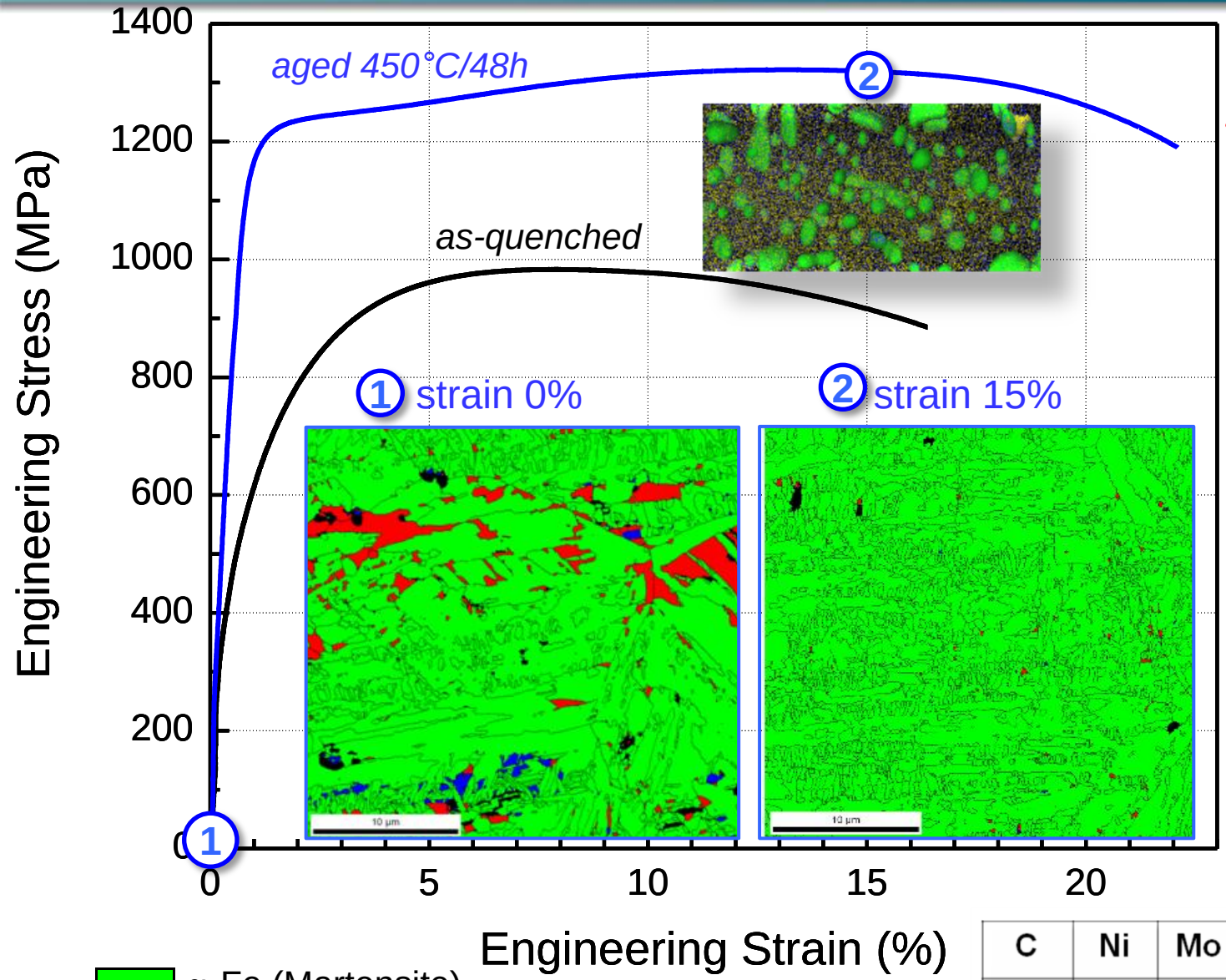
increase of austenite fraction during aging

α-Fe (Martensite)

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

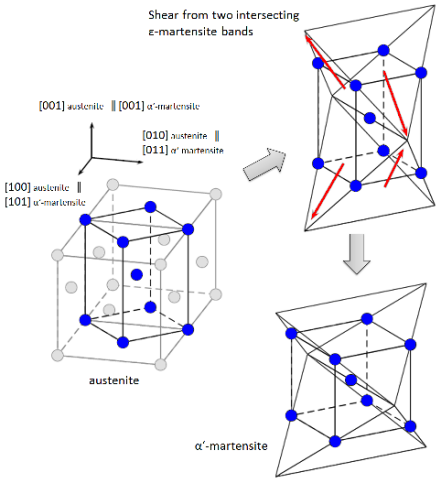
C	Ni	Mo	Ti	Al	Mn	Fe
0.01	2.0	1.0	1.0	0.15	12	bal.

Effect of aging on ductility



Precipitation hardening

increase? of austenite fraction during aging

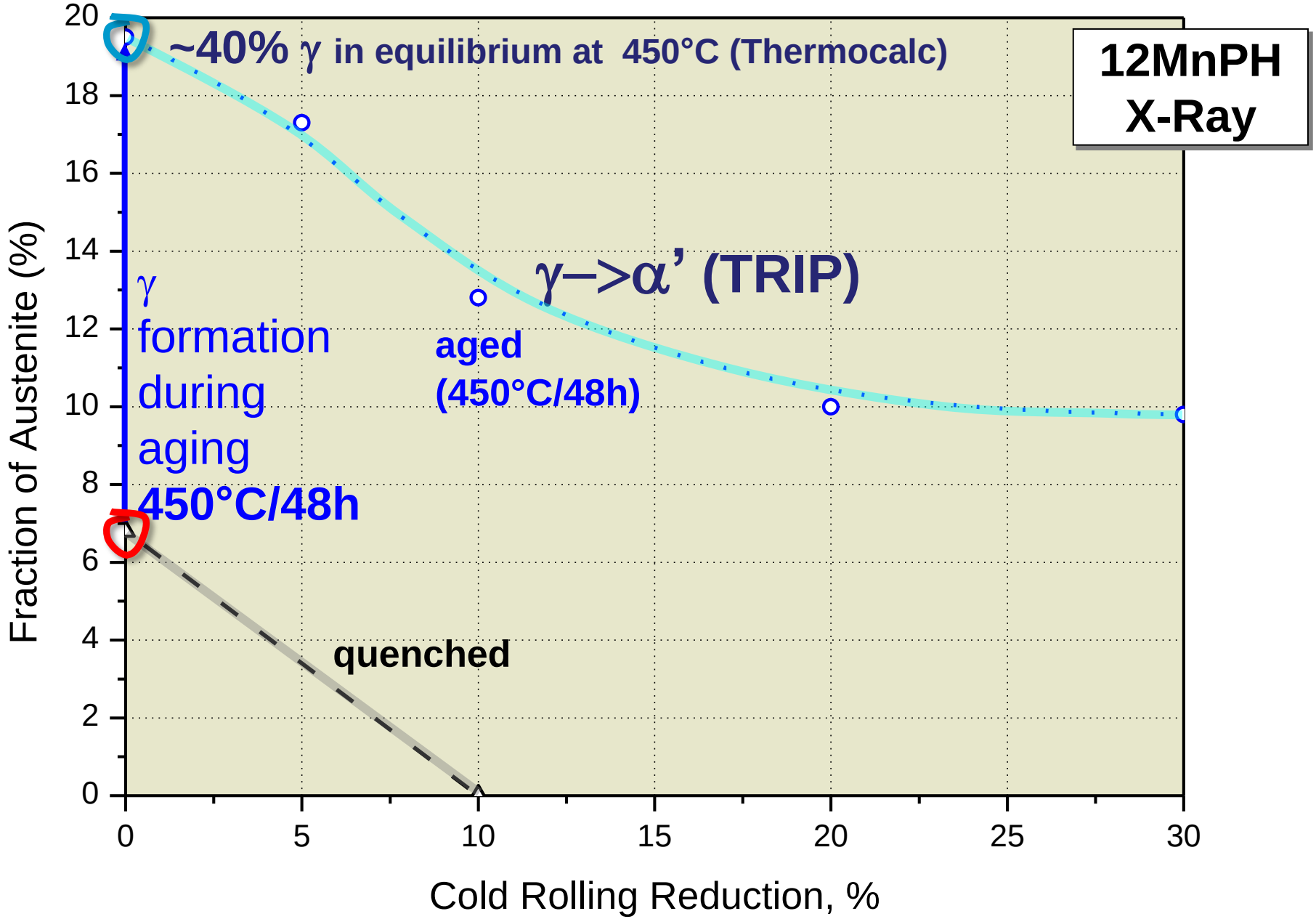


α-Fe (Martensite)

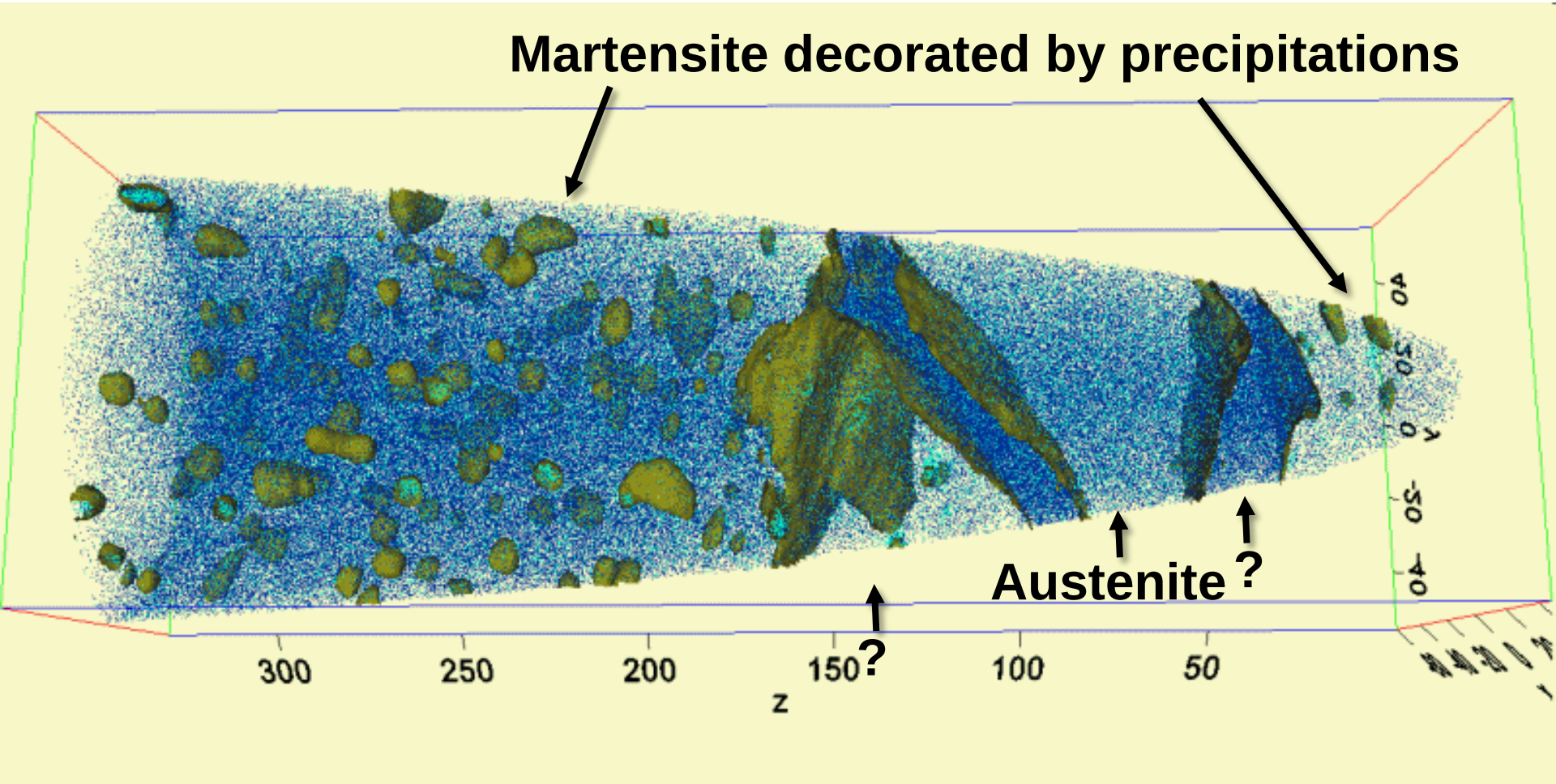
γ-Fe (Austenite), vol. fraction 15-20%

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

Effect of cold rolling after aging



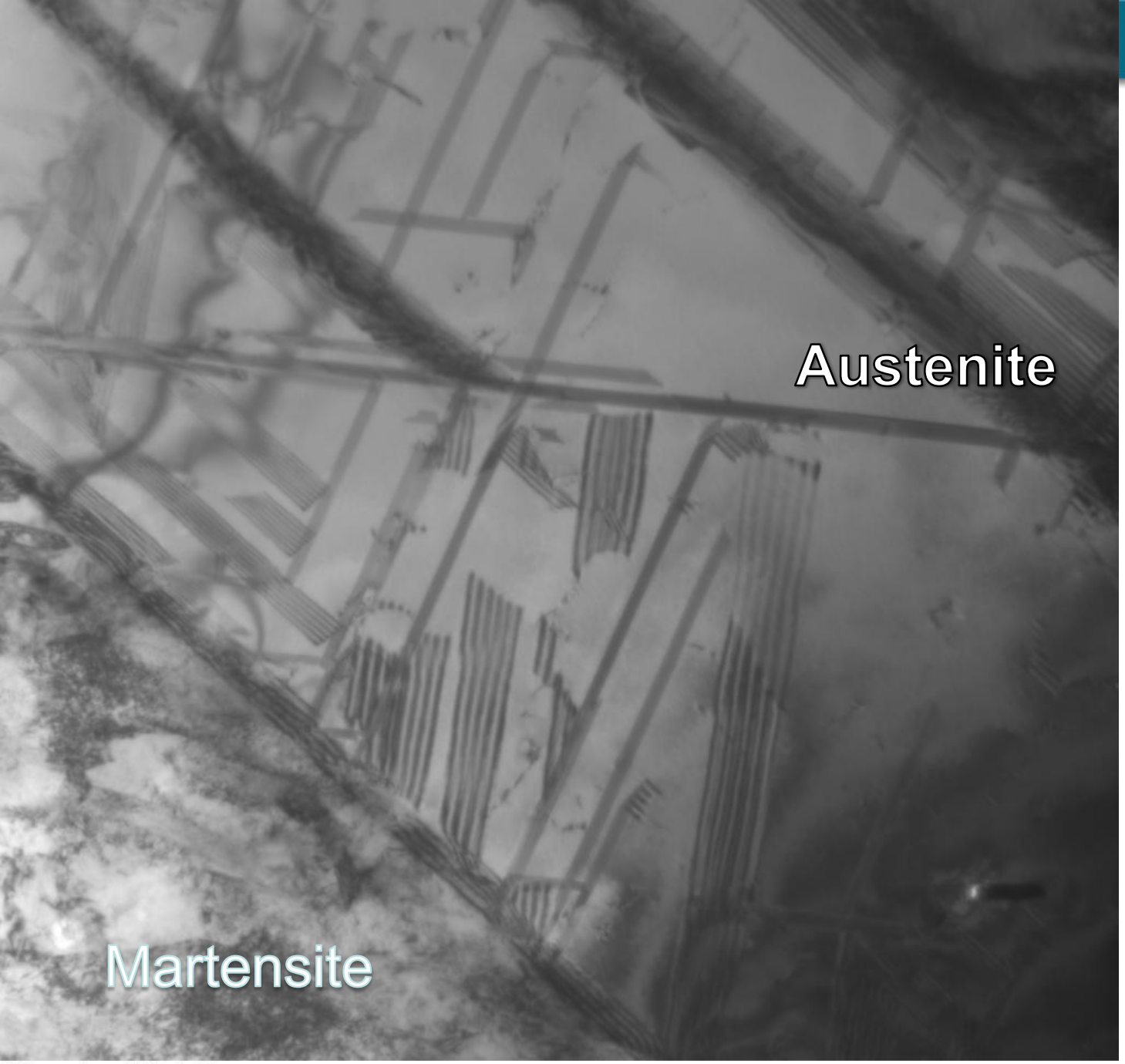
APT results: Atomic map (12MnPH aged 450°C/48h)



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)


Austenite
Martensite
PR_proben031.tif
PR13 65h@450 C
500 nm

Overview

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

Design of "Lean Maraging TRIP steel"

Precipitation hardening ⇨ Increase strength

Austenite (retained + new) ⇨ Increase ductility

- Martensitic Mn-steels (~0,01wt%C): good ductility
- + <u>controlled amounts</u> 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)