High Strength Forged Steel and Process Design

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Metallurgy for Forging Process Design and Tool Life Improvement vs. XRD Forum

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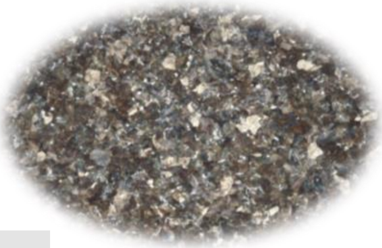
Outline

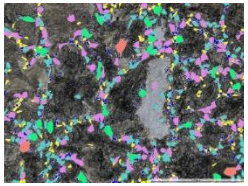
State of the Art

- Products from Microalloyed Forged Bars
- Microstructure of Air-Cooled Microalloyed Forged Steels
- Strength of Steel and Strengthening Mechanisms



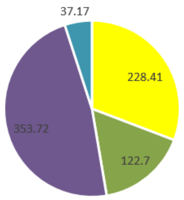
2 Method

- Industry-near Forging Experiment
- Metallography: LOM for phase fraction and grain size
- Mechanical Properties: tensile testing, hardness, impact
- Fraction of Precipitates: Synchrotron XAS



3 Results and Discussion

- Cooling Curves with Recalescence
- Calculated Contribution from each Strengthening Mechanism



Microalloyed Forged Steels

Typical Applications in Automotive Industry

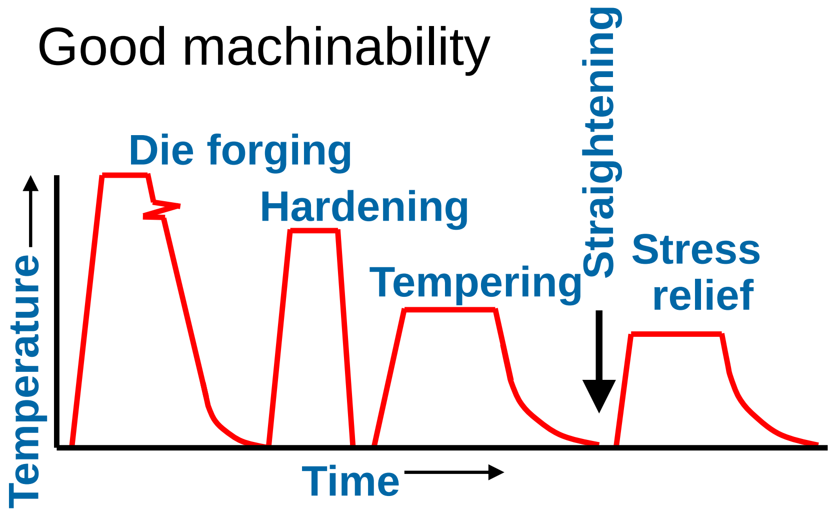
- Crankshaft
- Connecting rod
- Steering link
- Axle leg
- Wheel carrier
- Control arm
- Piston for diesel engines
- Common rail for diesel engines

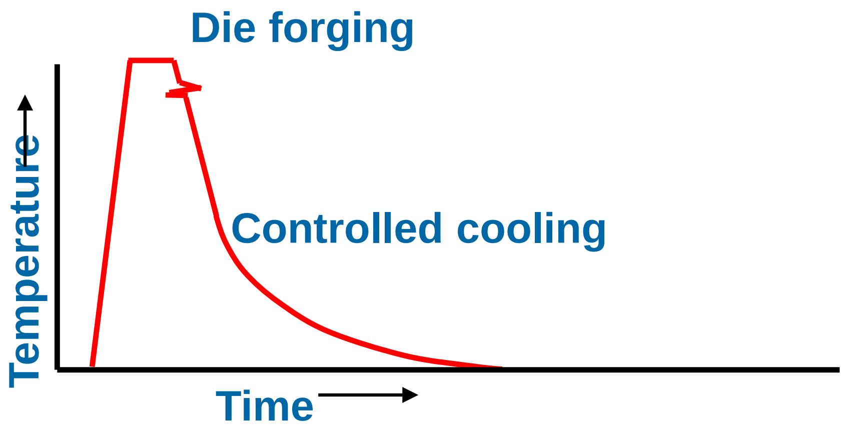
…

•**Source:** Basic Knowledge Forgings – Significance, Design, Production, Application, Industrieverband Massivumformung

Microalloyed Forged Steels

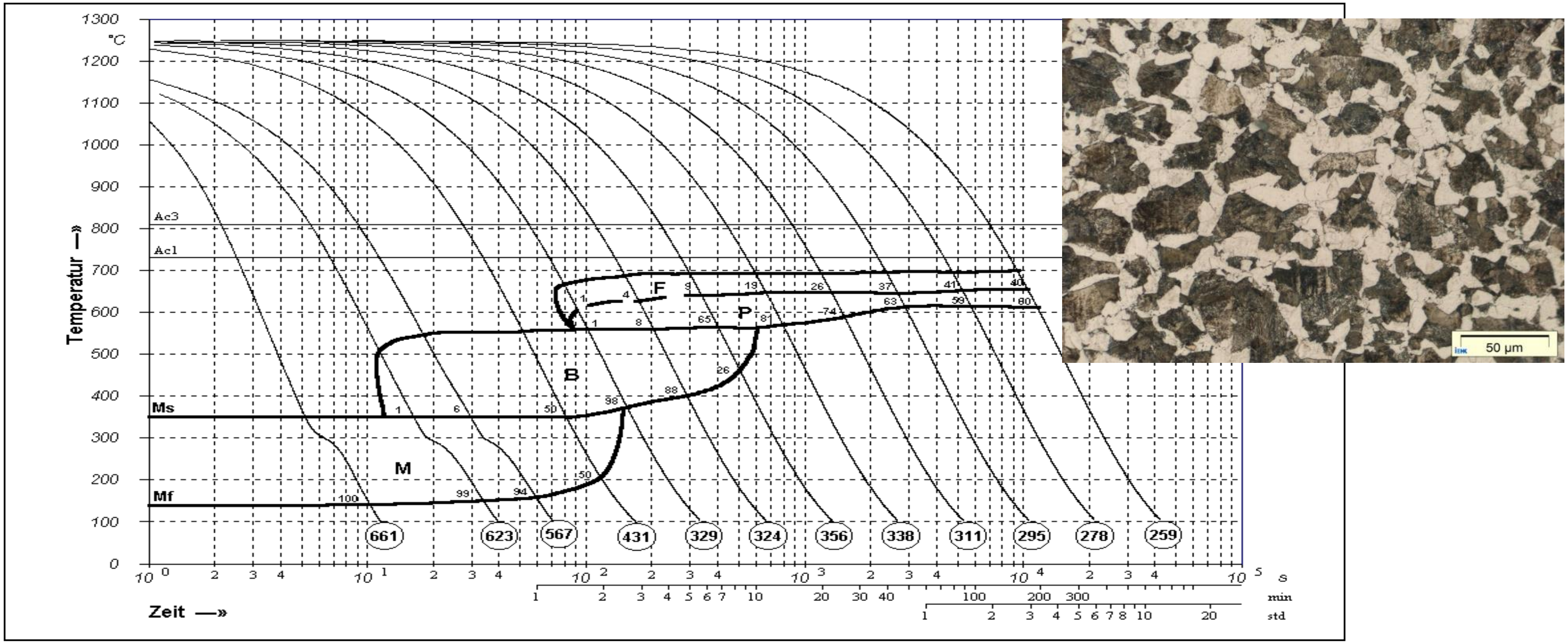
- Quenched and tempered steel (Q&T) needs an additional heat treatment (left picture)
- Microalloyed steels achieve final properties during controlled cooling directly after forging (right picture)
- Shorter process chain compared to Q&T steels → No costs for additional heat treatment
- No risk for crack formation during quenching
- Low cost alloying concept
- High strength
- Good machinability





Microalloyed Forged Steels

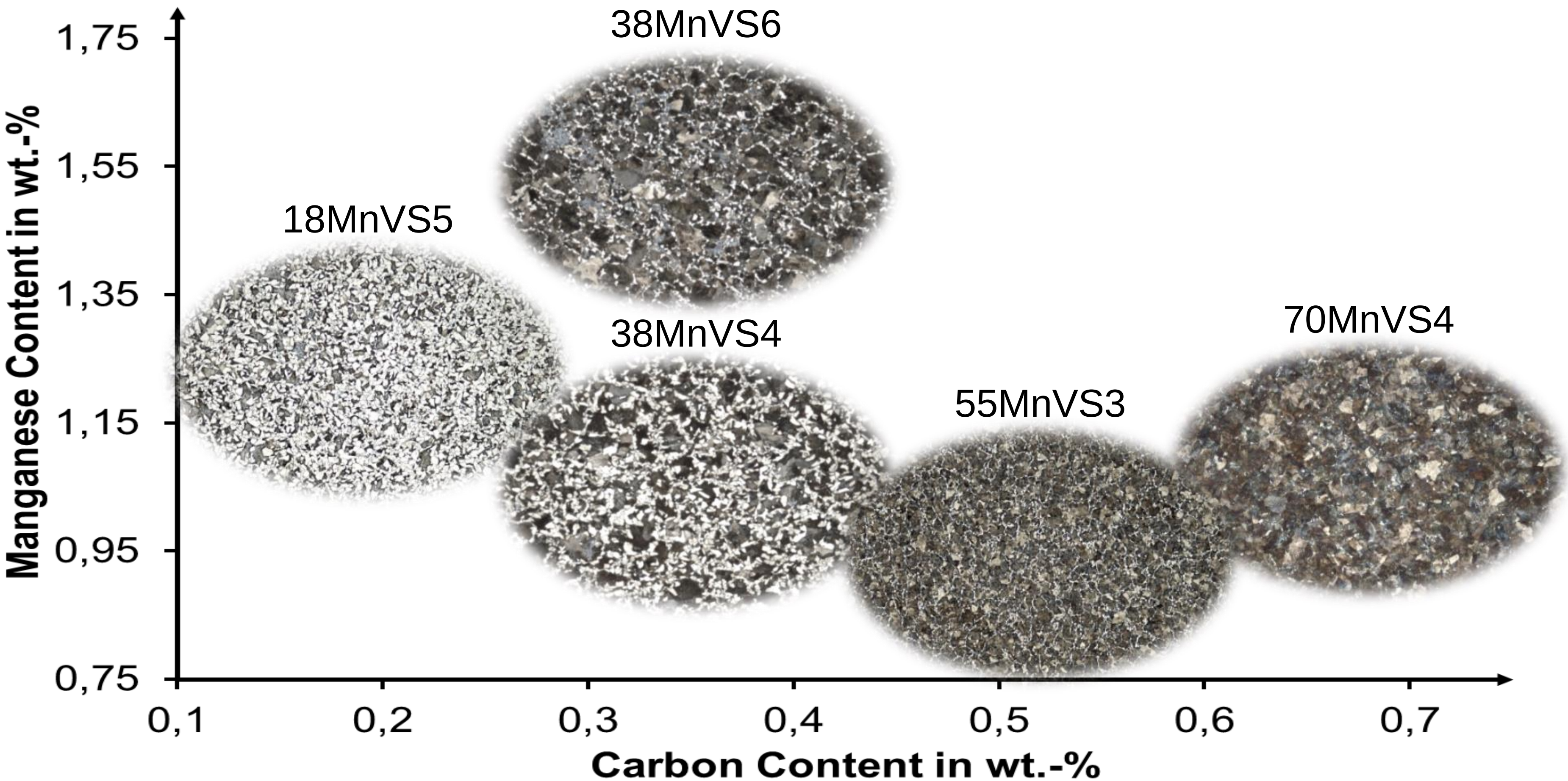
38MnVS6 as an example for a typical steel and its transformation behavior



Chemical Composition in wt.-%

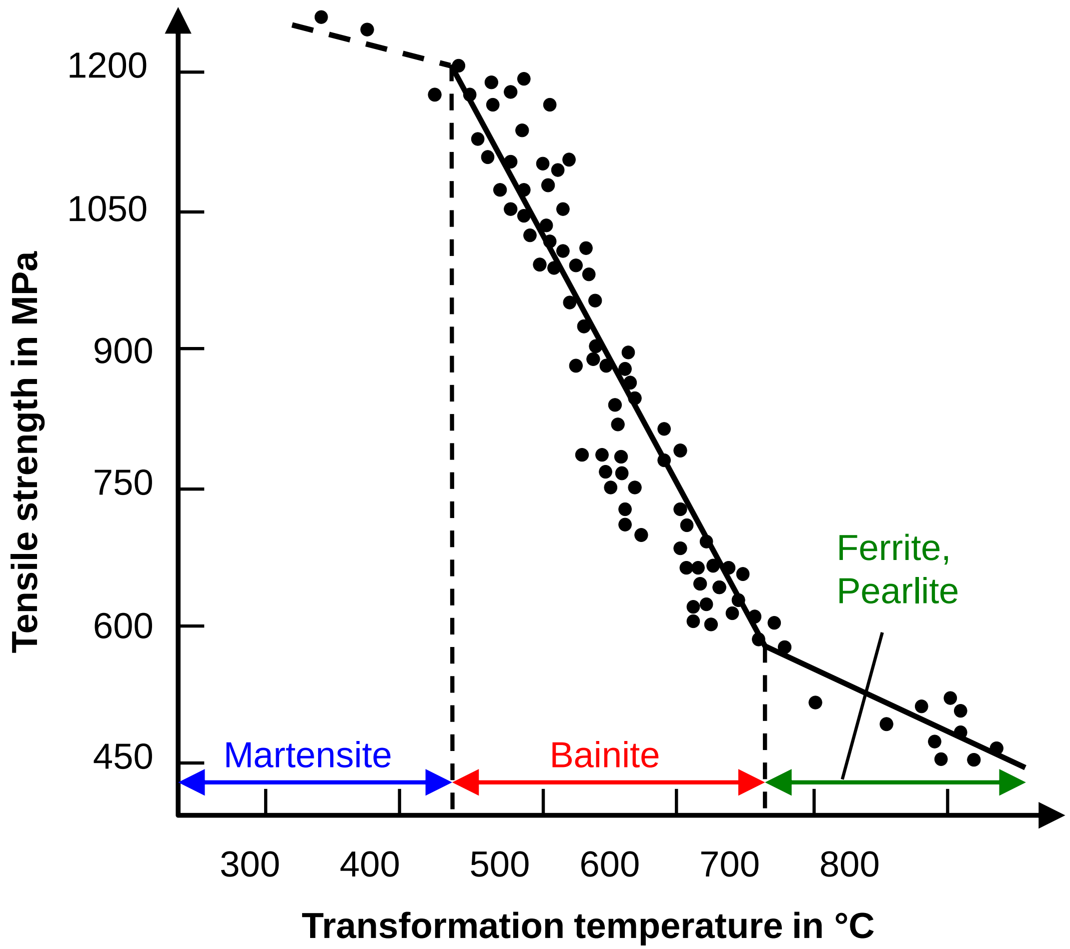
C	Si	Mn	P	S	Cr	Al	V	N
0,38	0,58	1,39	0,016	0,056	0,16	0,048	0,11	0,017

Microalloyed Forged Steels - Adjusting Phase Fractions



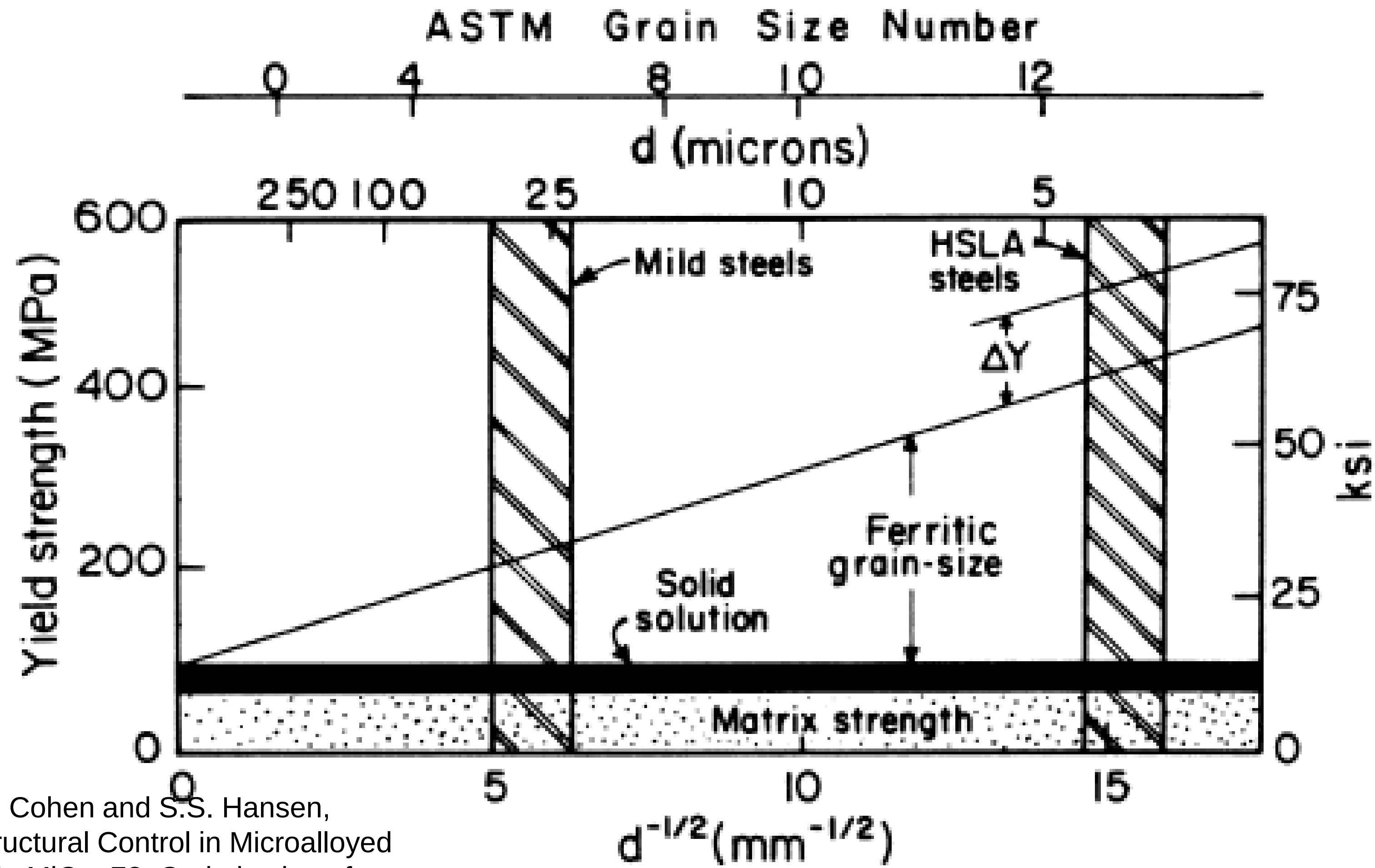
Source: H. Dickert et al, Steels in Cars and Trucks 2017

Strength of Different Matrices according to Pickering



Ref.: F.B. Pickering, in Transformation and Hardenability in Steels, Climax Molybdenum Co., Ann Arbor, Michigan, 1967, p. 109.

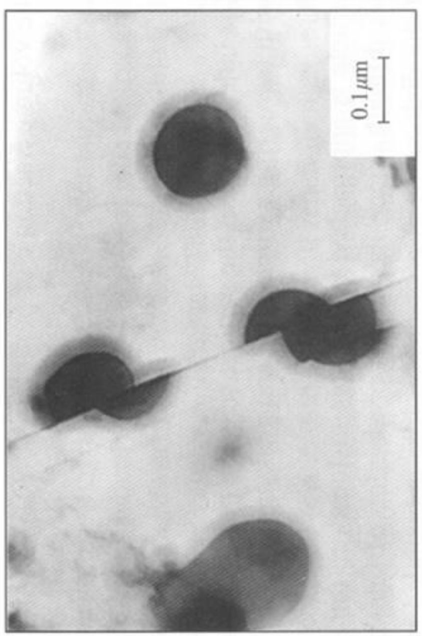
Contribution to Yield Strength in Mild and HSLA Steels

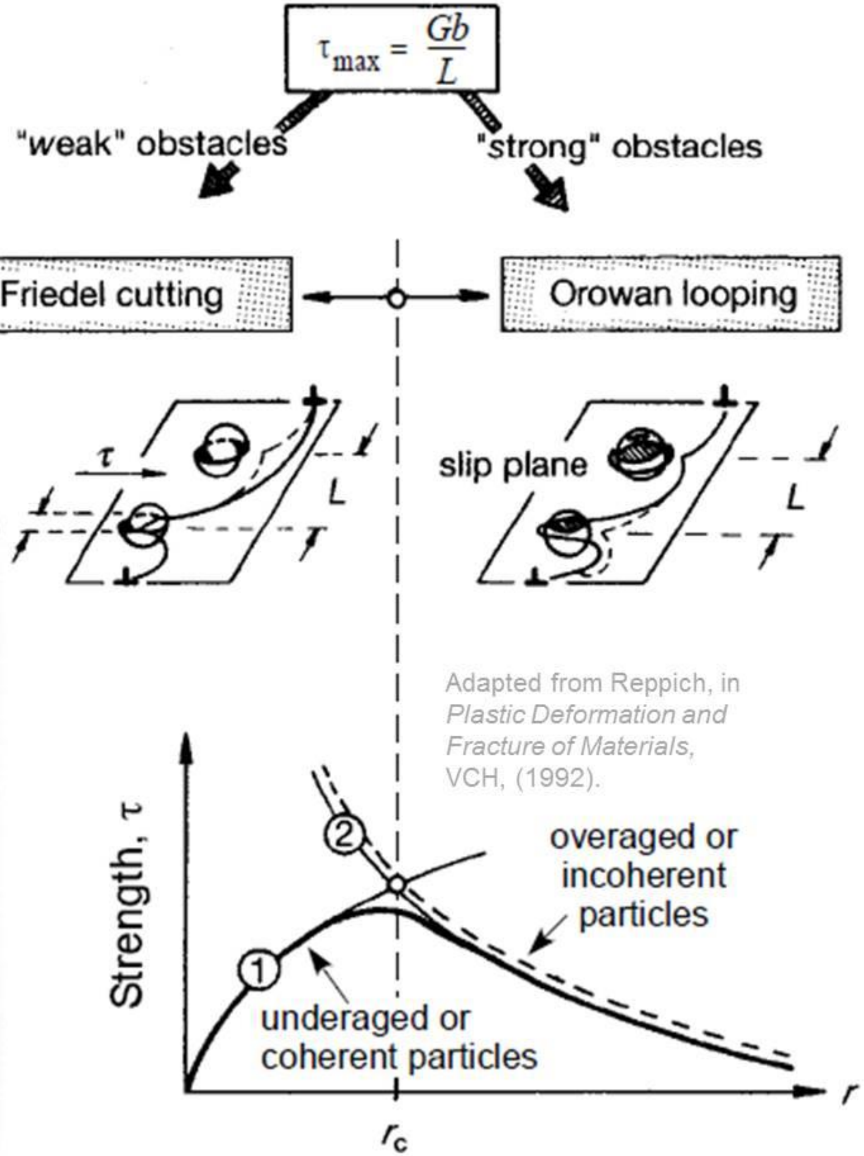


Ref. :M. Cohen and S.S. Hansen, Microstructural Control in Microalloyed Steels, in MiCon78: Optimization of Processing, Properties, and Service Performance Through icrostructural Control, ASTM STP 672, H. Abrams, G.N. Maniar, D.A. Nail and H.D. Solomon, Ed., 1979, p 34–52

Precipitation Hardening: Cutting vs. Looping

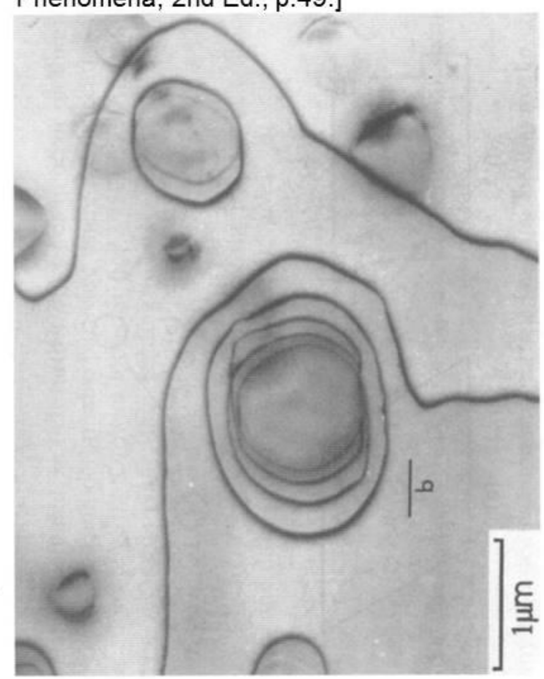
Argon, Strengthening Mechanisms in Crystal Plasticity., p.221





Adapted from Reppich, in *Plastic Deformation and Fracture of Materials*, VCH, (1992).

Ref.: Humphreys and Hatherly, Recrystallization and Related Annealing Phenomena, 2nd Ed., p.49.]

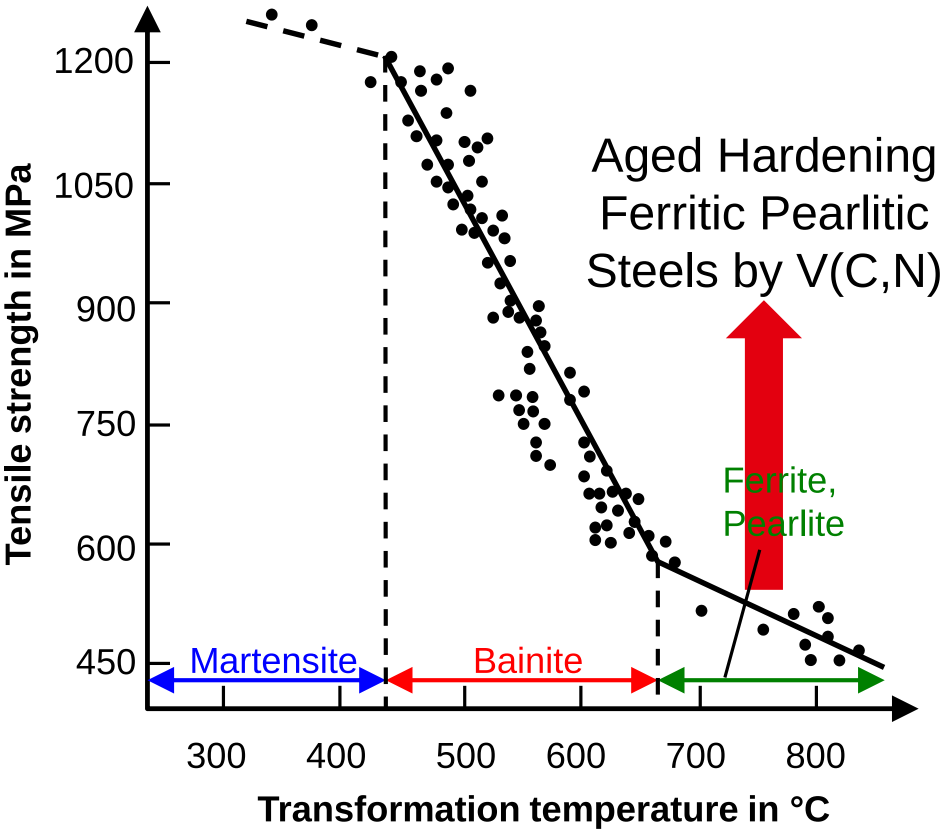


Precipitation Hardening in Ferrite-Pearlite

$$YS = f_\alpha\{35 + 58(\%Mn) + 17.4(D_\alpha)^{-0.5}\} + (1 - f_\alpha)\left\{178 + 3.8(\lambda_p)^{-0.5}\right\} + 63(\%Si) + 425(\%N)^{-0.5} + \Delta YS_p$$

$$\Delta YS_{p,Orowan-Ashby}$$

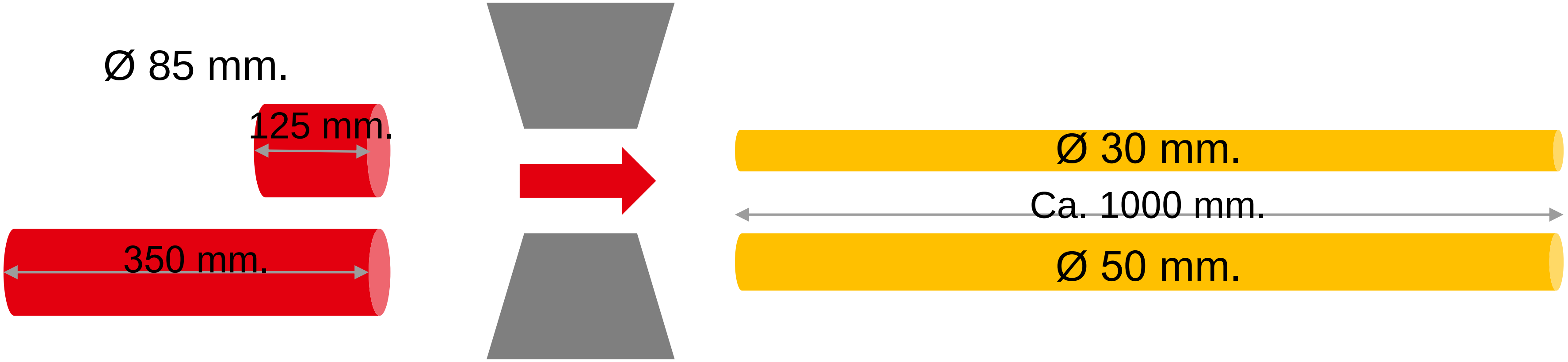
)



S. Zajac, T. Siwecki, W.B. Hutchinson and R. Lagneborg: Strengthening Mechanisms in Vanadium Microalloyed Steels Intended for Long Products, ISIJ international 38.10 (1998), pp. 1130-1139

Method: Industrial Cast and Forging Experiments

C	Si	Mn	P	S	Cu	Al	Cr	Mo	Ni	N	V	Ti
0.37	0.59	1.05	0.013	0.025	0.11	0.016	0.17	0.04	0.11	0.013	0.268	0.018



Industrial Process

- Final Cooling on the conveyor belt is controlled by:
  - Speed of the conveyor belt
  - Use of fans (to increase cooling rate)
  - Covering the conveyor belt (to reduce the cooling rate).

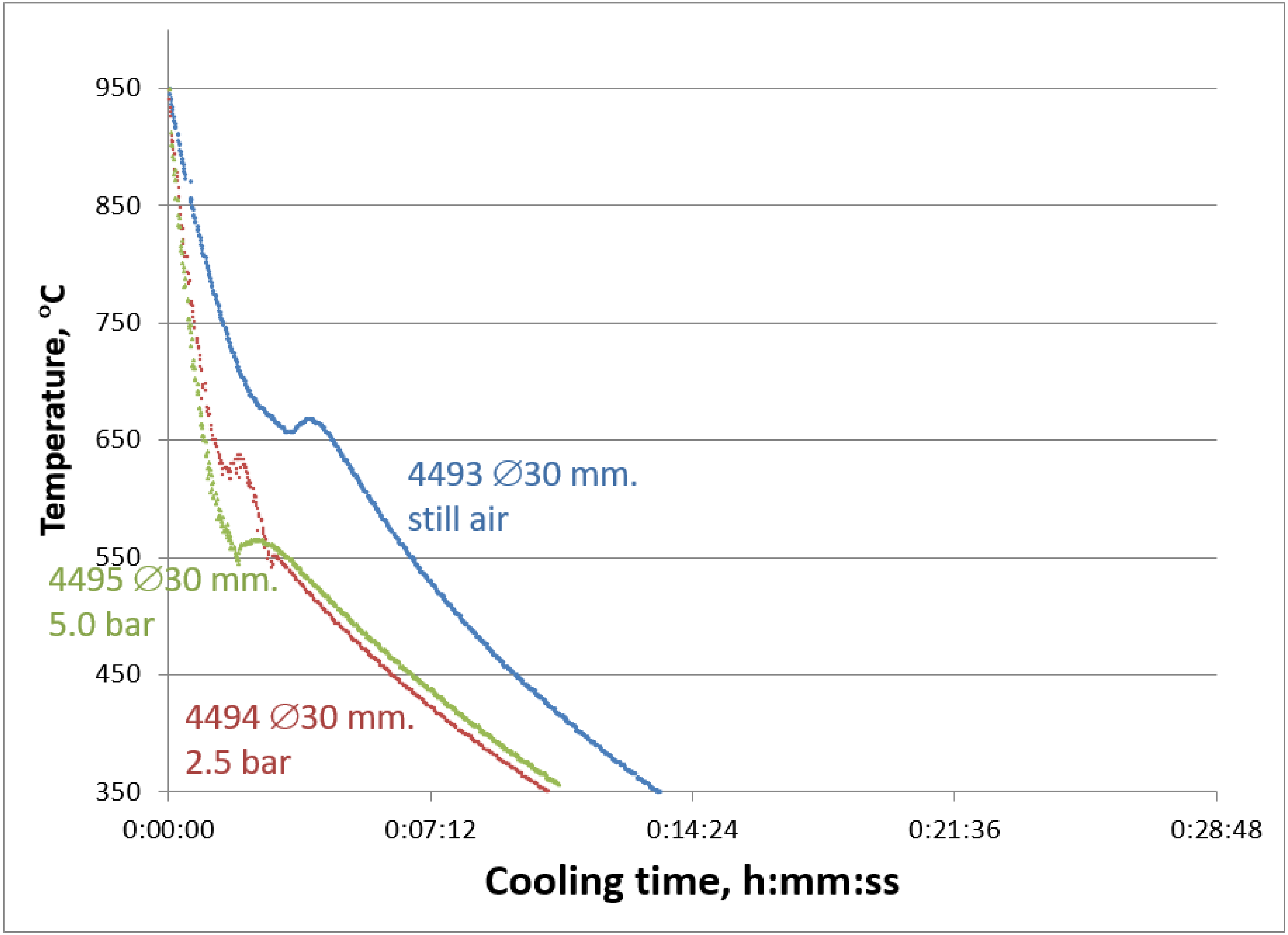
Method: Industry-near Process

- Open die manual forging on a forging hammer
- Controlled cooling by using different pressures of compre
- Temperature measurement with a pyrometer

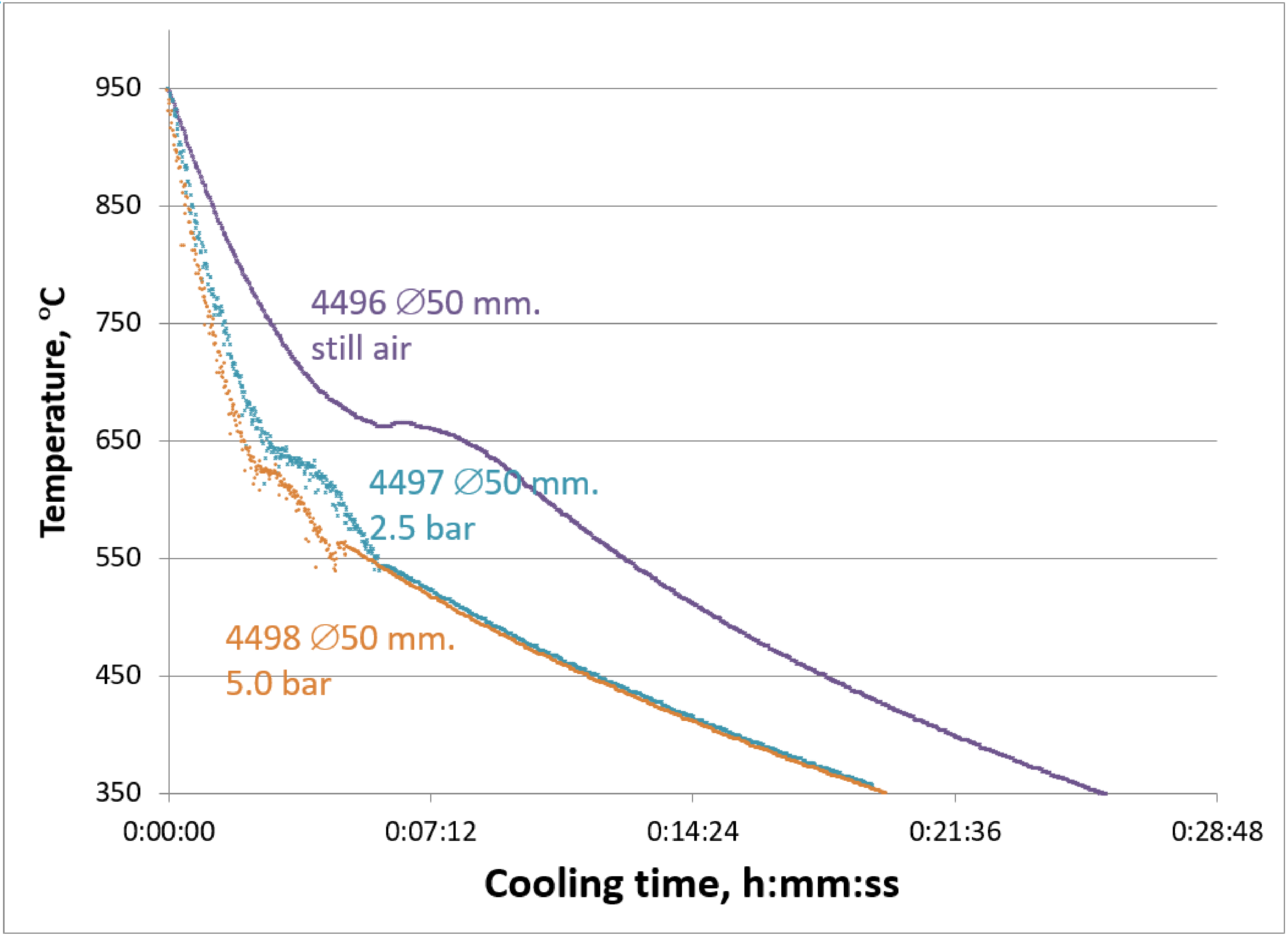
CONFIDENTIAL

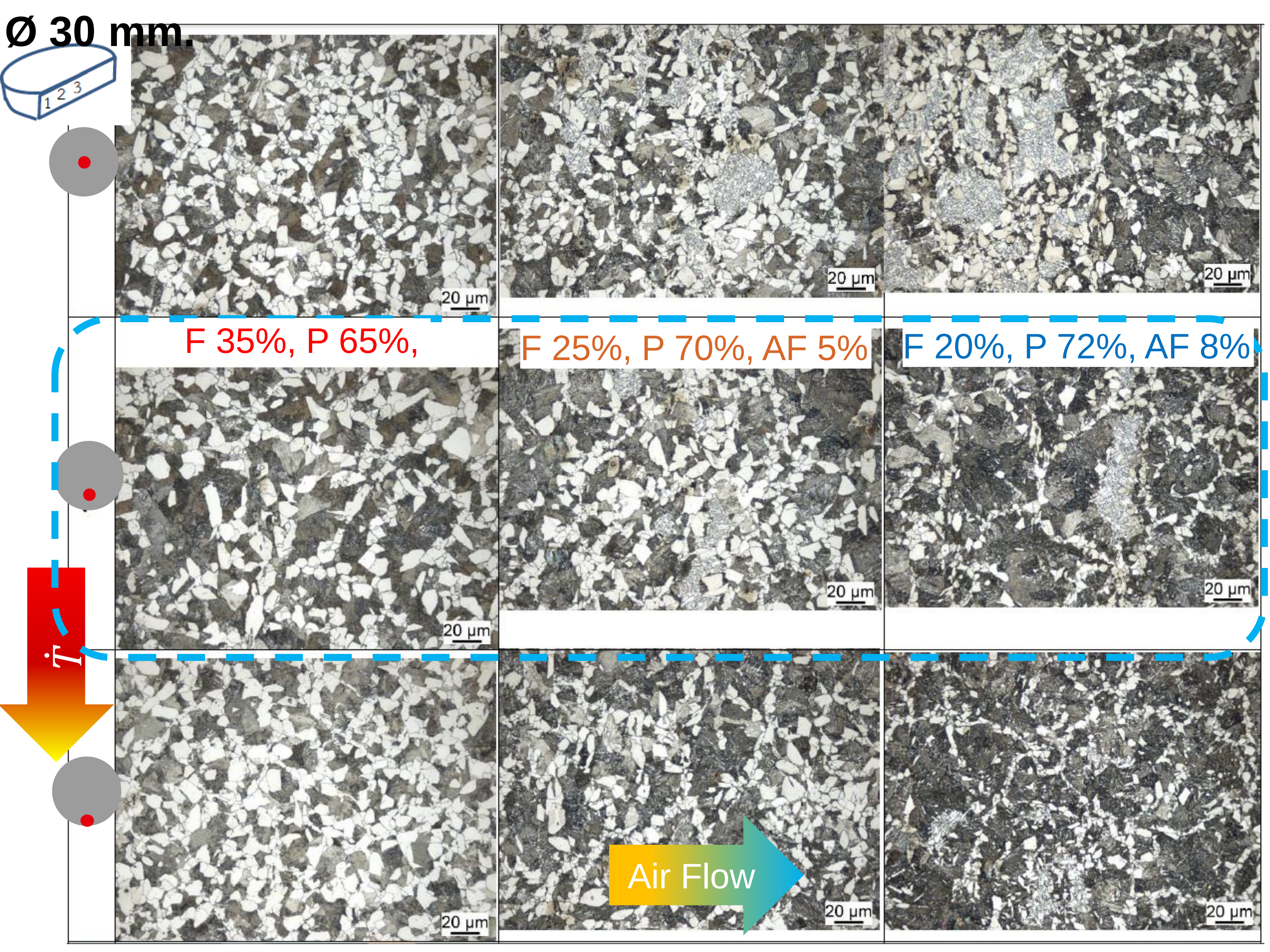
No Photography

Results: Cooling Curves with Recalescence

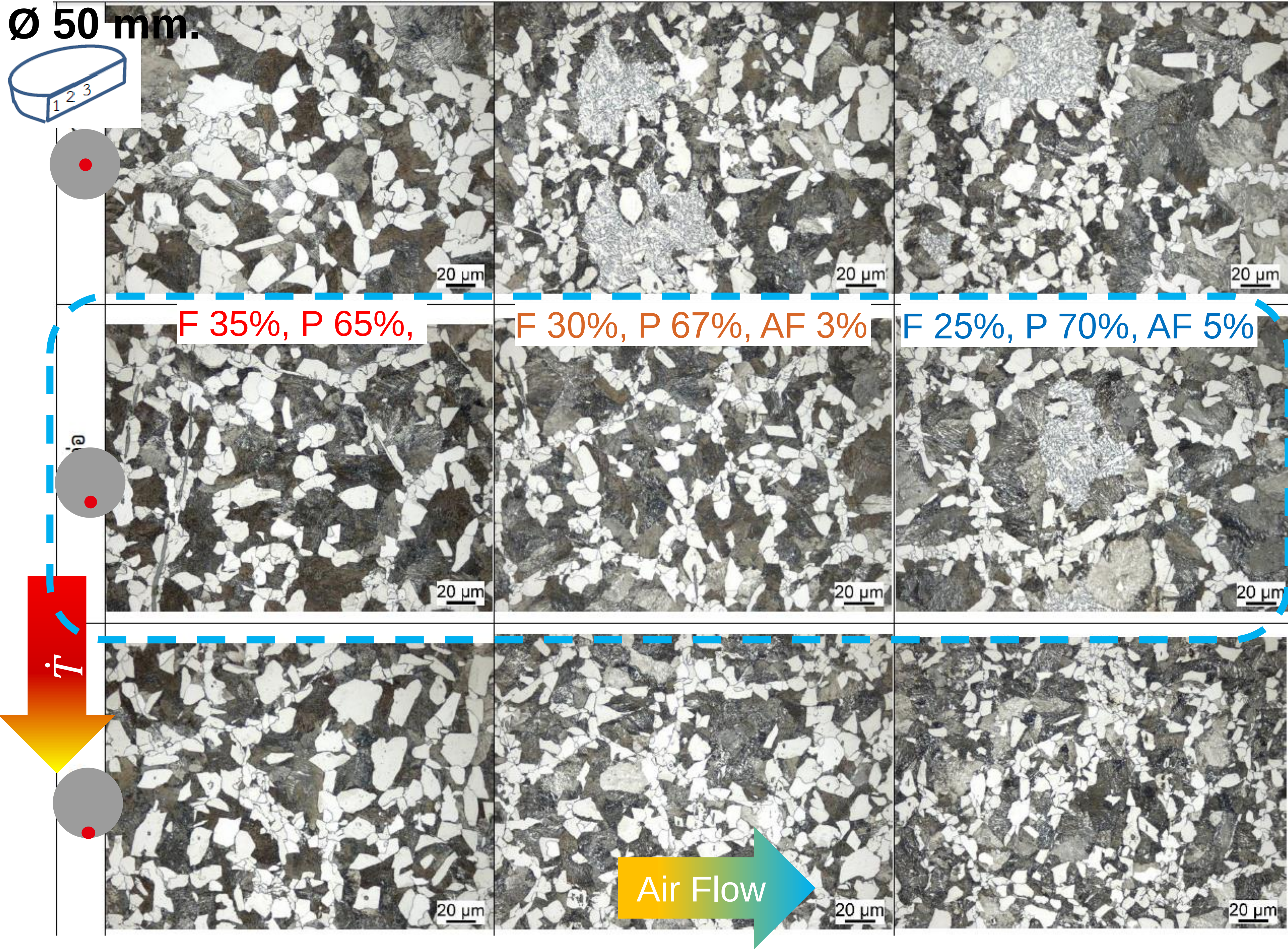


Results: Cooling Curves with Recalescence

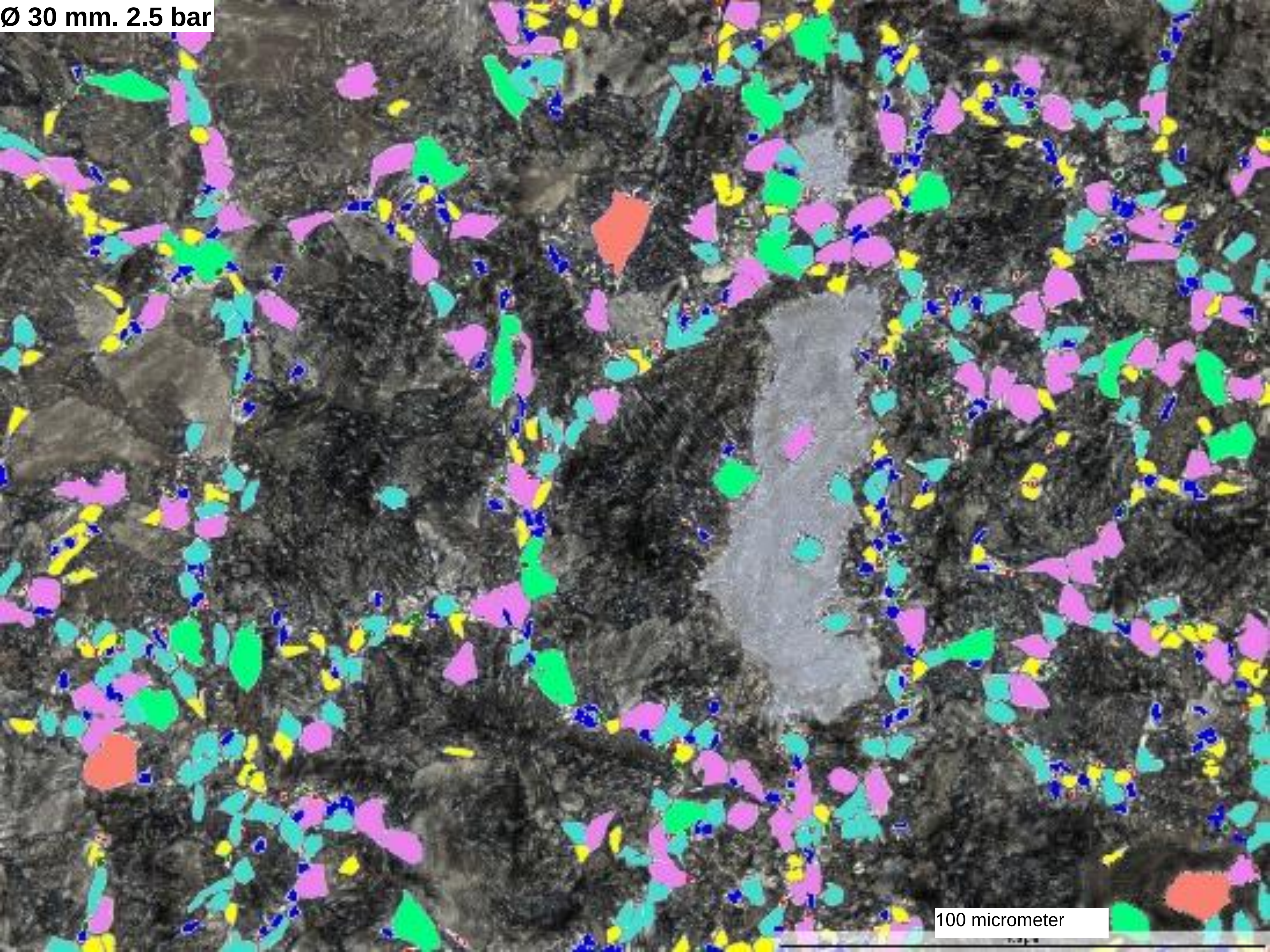




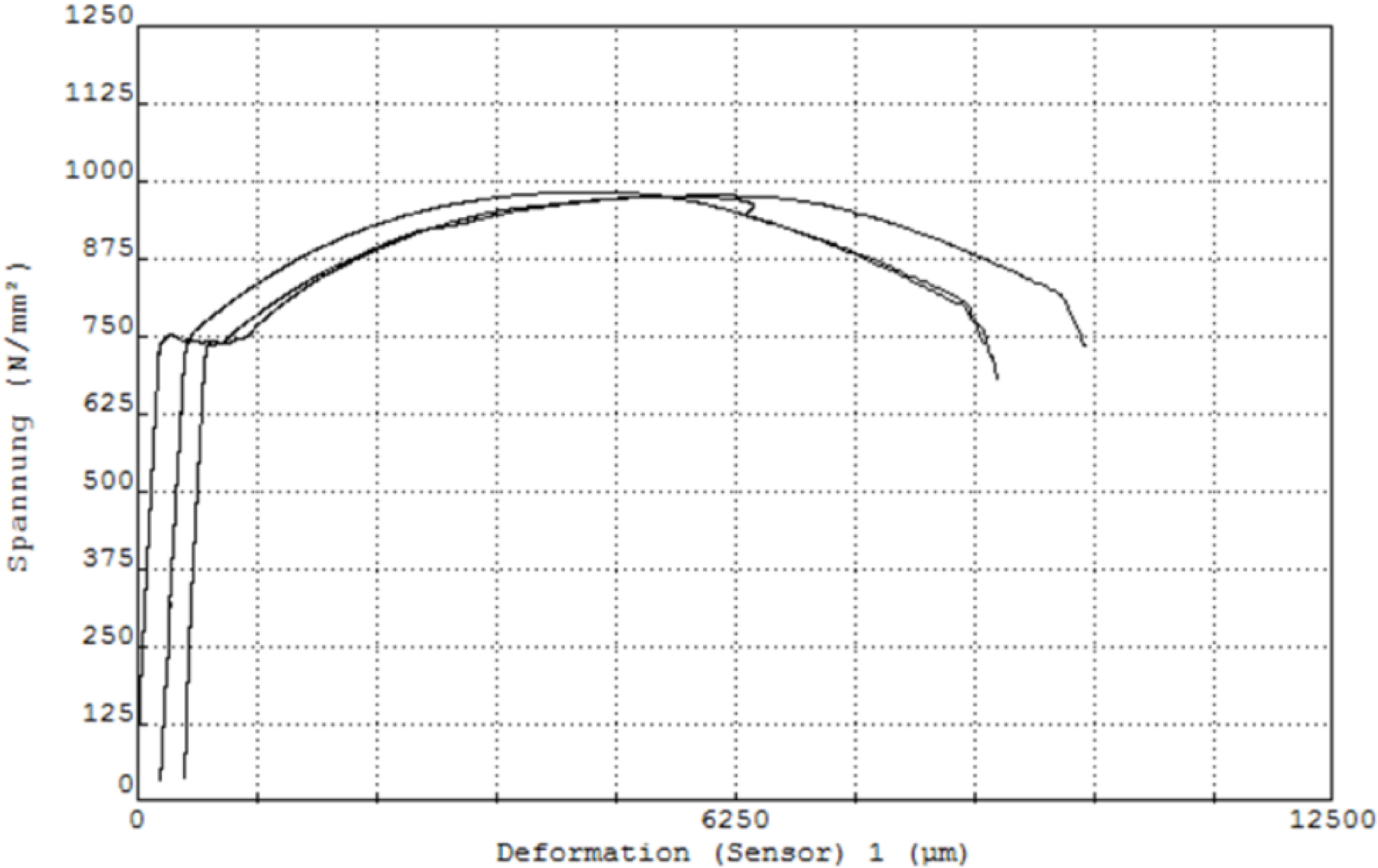
Ø 30 mm.
1 2 3
F 35%, P 65%,
F 25%, P 70%, AF 5%
F 20%, P 72%, AF 8%
$\dot{T}$
Air Flow
20 µm

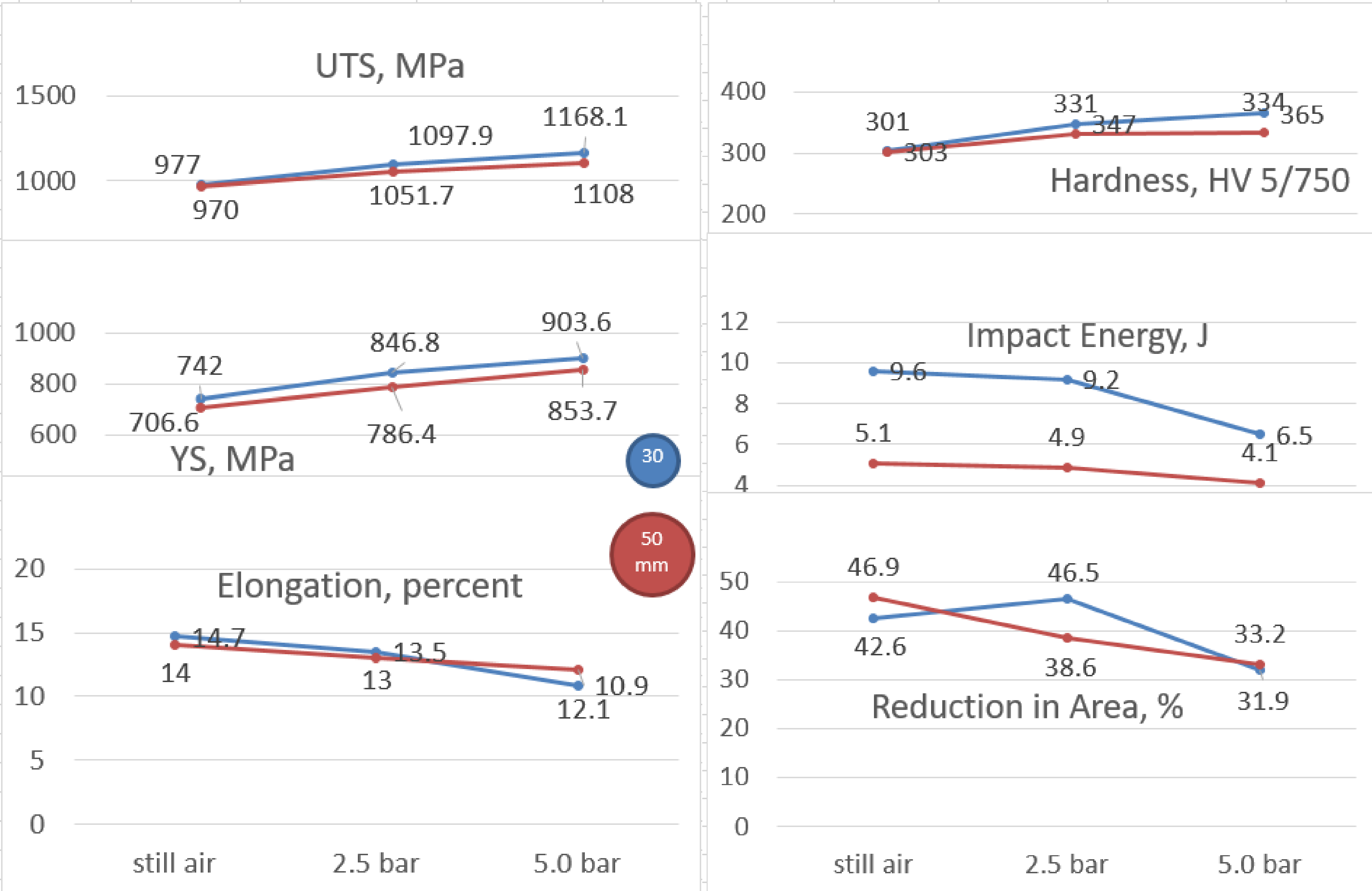


Ø 50 mm.
1 2 3
F 35%, P 65%,
F 30%, P 67%, AF 3%
F 25%, P 70%, AF 5%
$\dot{T}$
Air Flow
20 µm


Ø 30 mm. 2.5 bar
100 micrometer

Ø 30 mm. still air



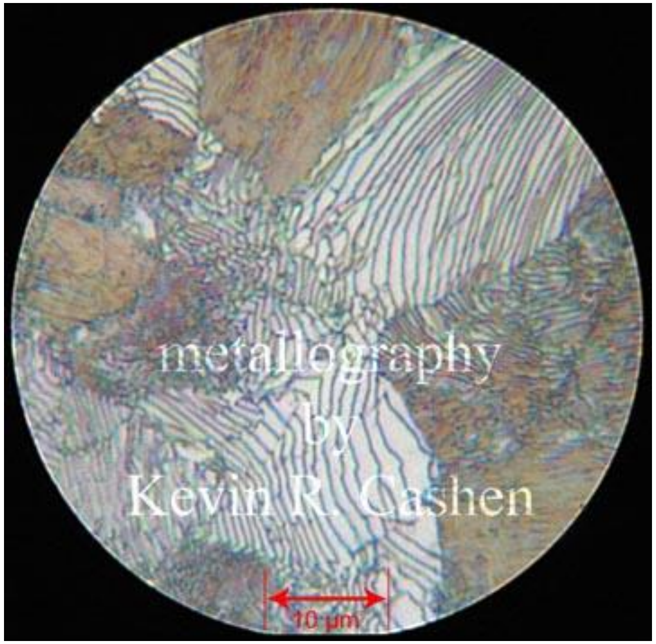


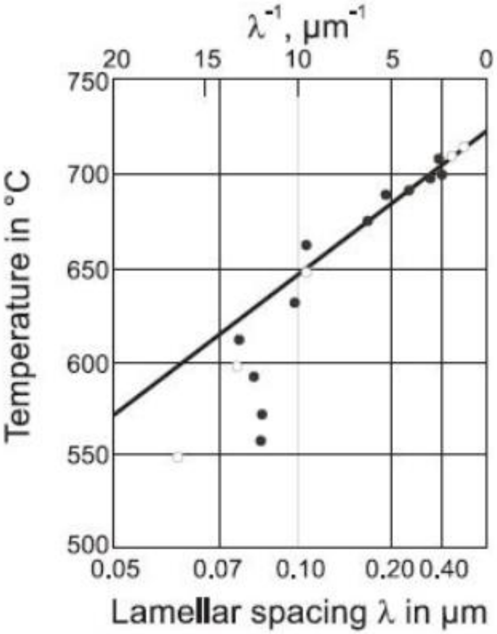
UTS, MPa
1500
1000
977
970
1097.9
1051.7
1168.1
1108
Hardness, HV 5/750
400
300
200
301
303
331
347
334
365
YS, MPa
1000
800
600
742
706.6
846.8
786.4
903.6
853.7
Impact Energy, J
12
10
8
6
4
9.6
5.1
9.2
4.9
6.5
4.1
30
50
mm
Elongation, percent
20
15
10
5
0
14.7
14
13.5
13
10.9
12.1
Reduction in Area, %
50
40
30
20
10
0
46.9
42.6
46.5
38.6
33.2
31.9
still air
2.5 bar
5.0 bar
still air
2.5 bar
5.0 bar

Calculation of Strengthening Factors

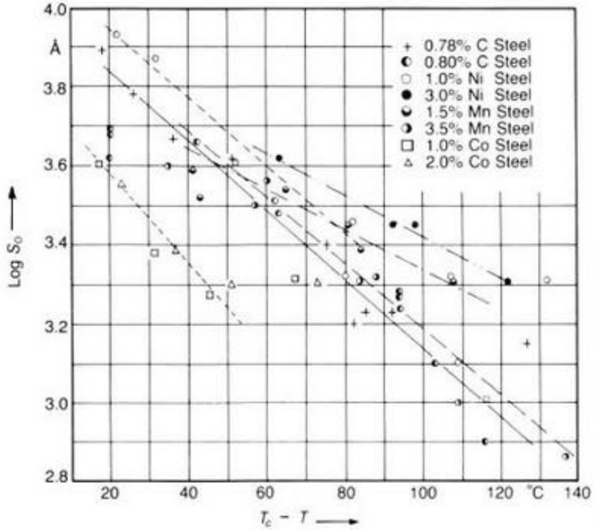
$$YS = f_\alpha\{35 + 58(\%Mn) + 17.4(D_\alpha)^{-0.5}\} + (1 - f_\alpha)\left\{178 + 3.8\left(\lambda_p\right)^{-0.5}\right\} + 63(\%Si) + 425(\%N)^{-0.5} + \Delta YS_p$$

Calculation of the Pearlite Interlamellar Spacing





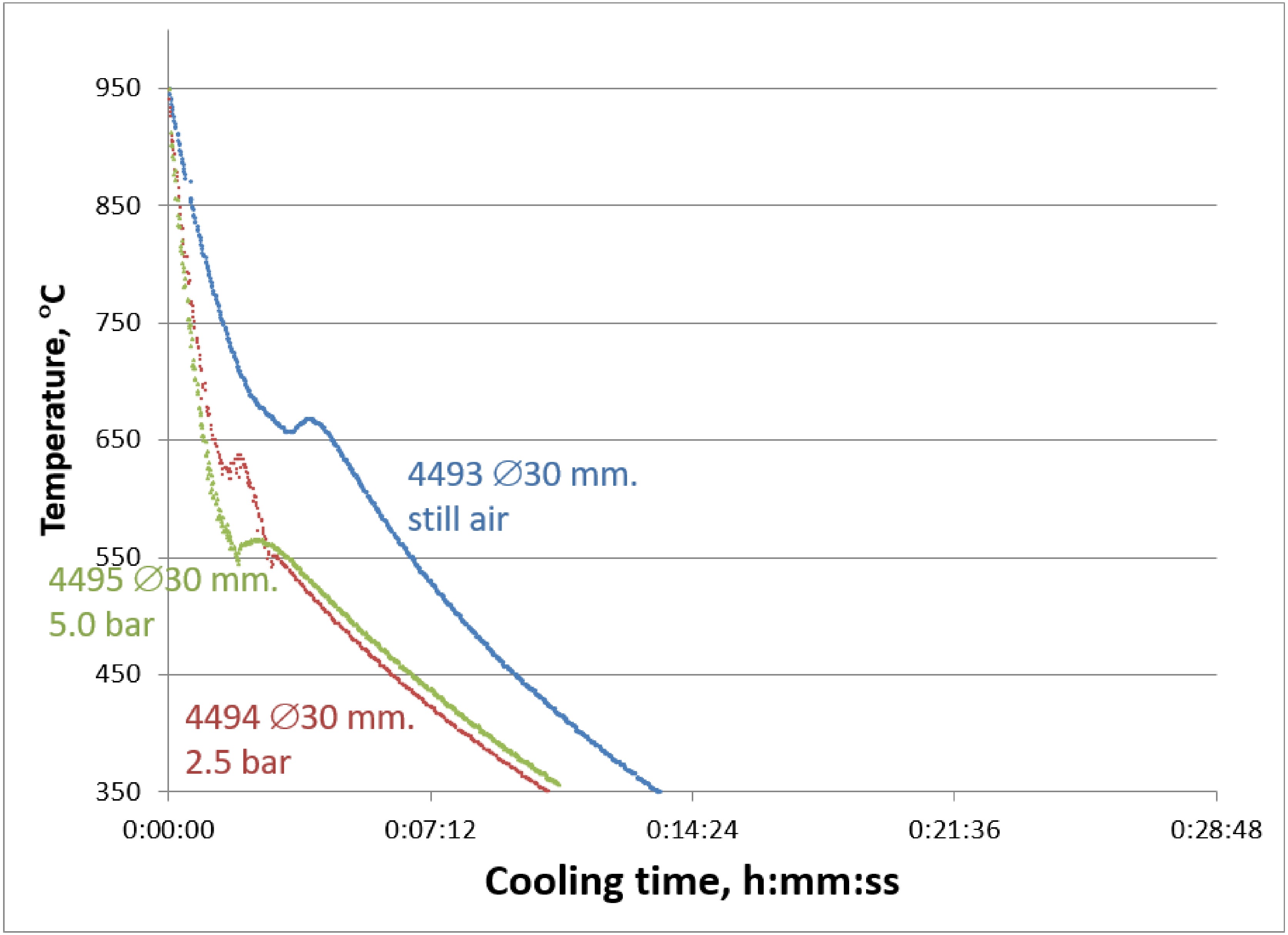
Bleck



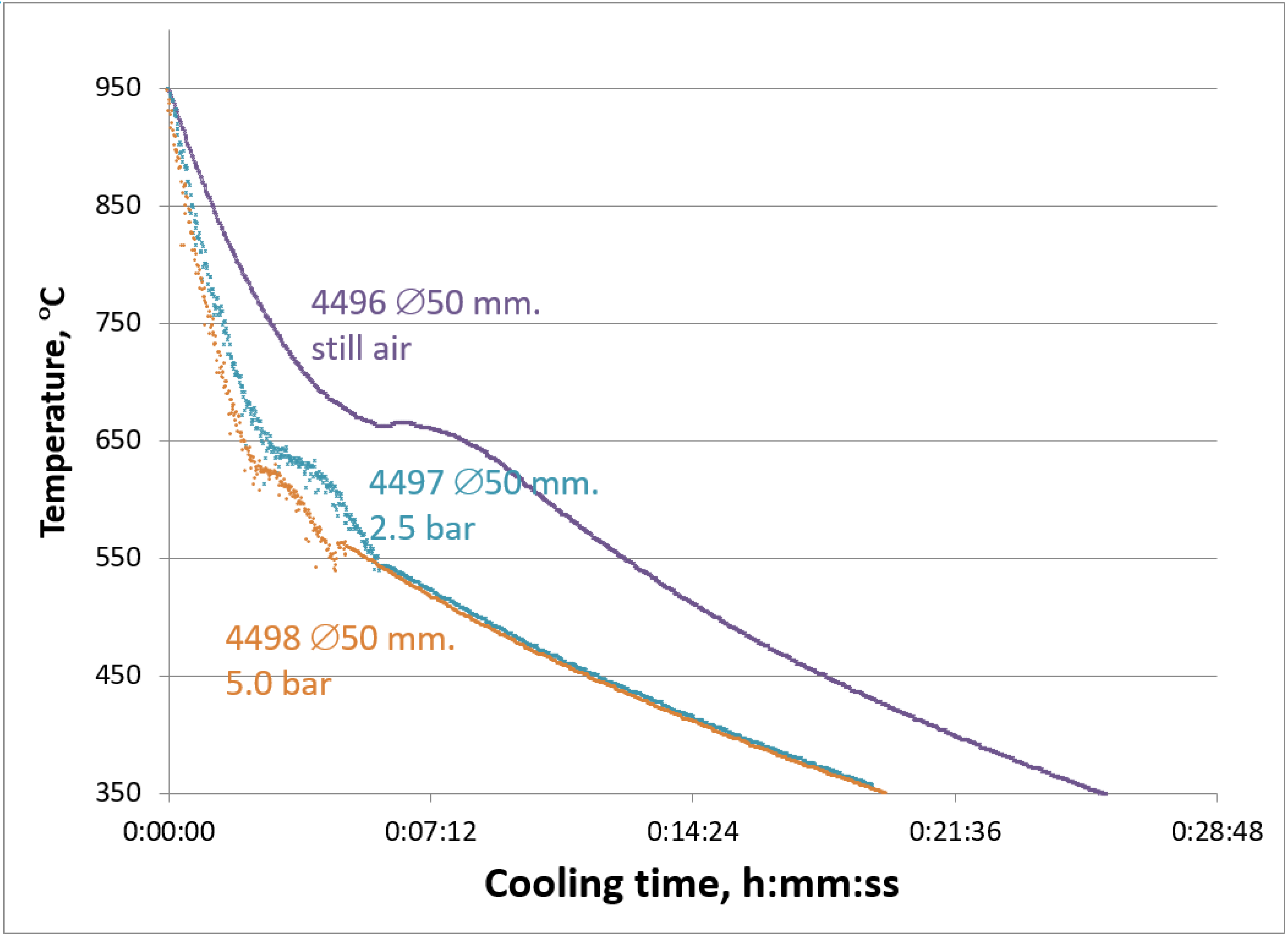
Mehl and Hagel

$$\lambda = \frac{7}{\Delta T}$$

Results: Cooling Curves with Recalescence



Results: Cooling Curves with Recalescence



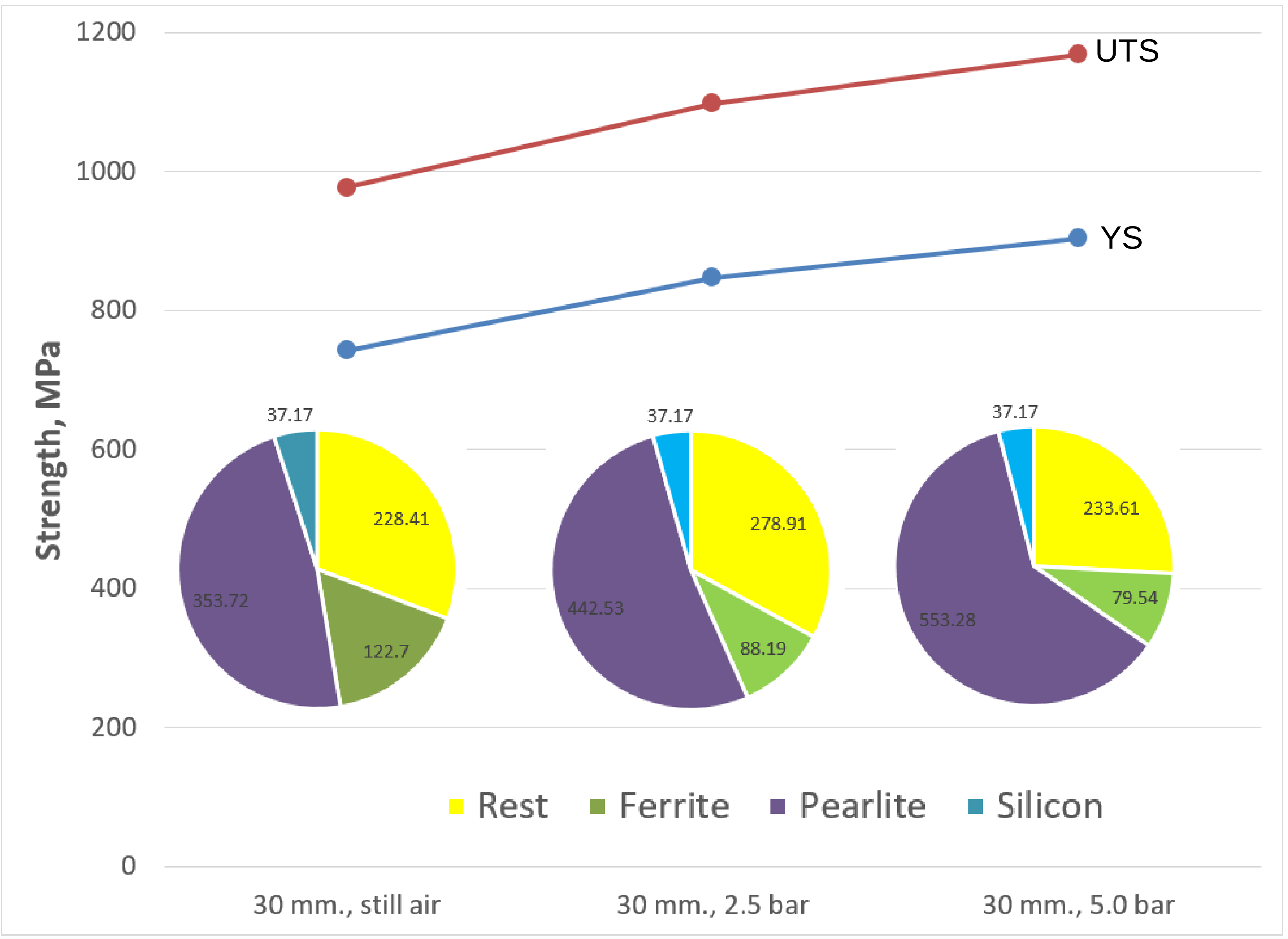
Calculation of the Precipitation Hardening

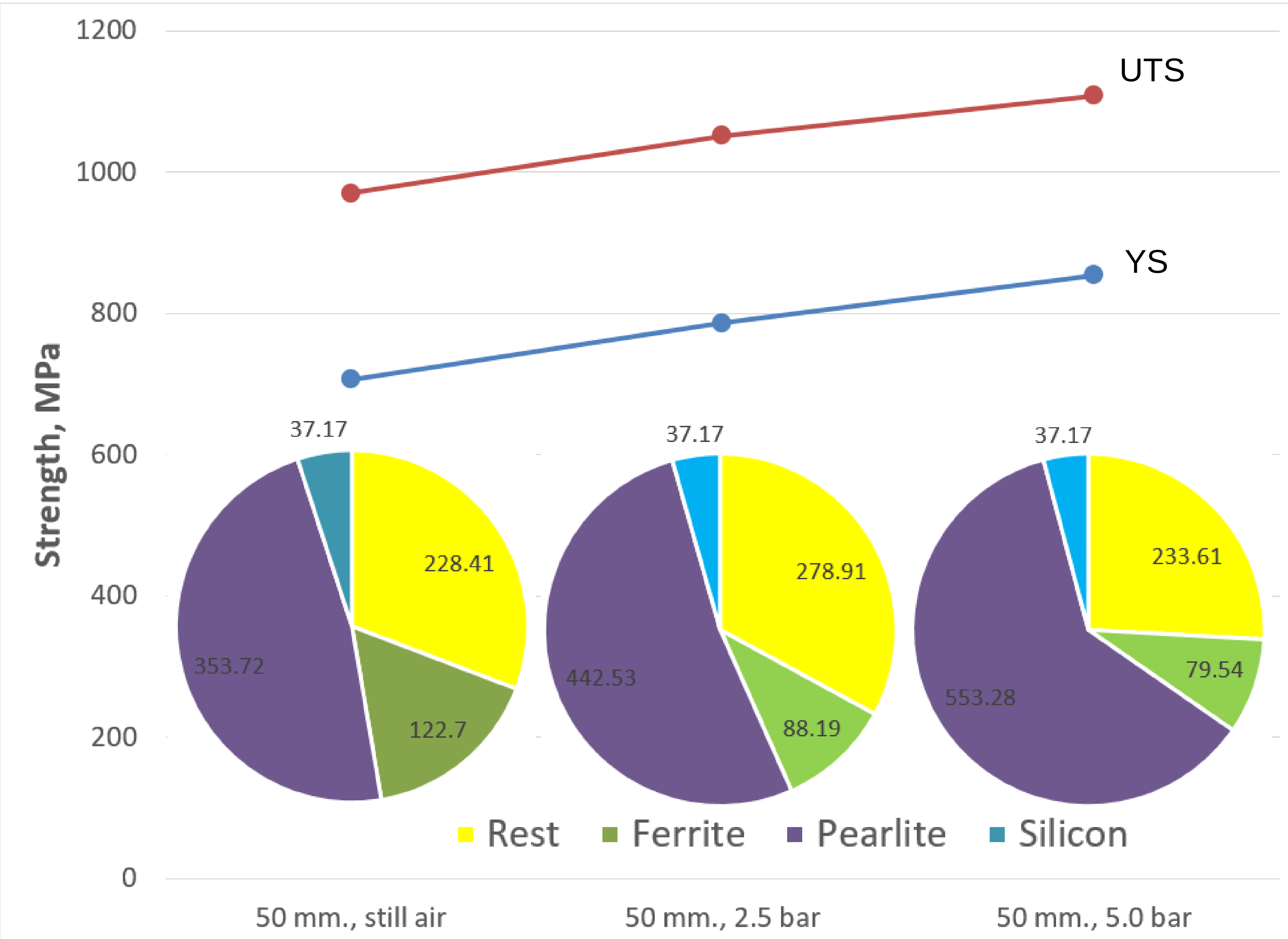
$$YS = f_\alpha\{35 + 58(\%Mn) + 17.4(D_\alpha)^{-0.5}\} + (1 - f_\alpha)\left\{178 + 3.8\left(\lambda_p\right)^{-0.5}\right\} + 63(\%Si) + 425(\%N)^{-0.5} + \Delta YS_p$$

$$\Delta YS_{p,Orowan-Ashby} = \frac{0.8MGb}{2\pi\sqrt{1-\nu}L_{VC}}\ln\left(\frac{x}{2b}\right)\ (MPa)$$

$$L_{VC} = \sqrt{\frac{2}{3}}\left(\sqrt{\frac{\pi}{f}} - 2\right) r_{VC} (m \qquad x = 2\sqrt{\frac{2}{3}} r_{VC}$$

M – Tailor Factor, G – Shear modulus, b – Burger vector, ν - Poison's ratio


UTS
YS
Strength, MPa
1200
1000
800
600
400
200
0
37.17
228.41
122.7
353.72
37.17
278.91
88.19
442.53
37.17
233.61
79.54
553.28
Rest
Ferrite
Pearlite
Silicon
30 mm., still air
30 mm., 2.5 bar
30 mm., 5.0 bar



1200
1000
800
600
400
200
0
Strength, MPa
UTS
YS
37.17
228.41
122.7
353.72
37.17
278.91
88.19
442.53
37.17
233.61
79.54
553.28
Rest
Ferrite
Pearlite
Silicon
50 mm., still air
50 mm., 2.5 bar
50 mm., 5.0 bar

The 2 Unknown Strengthening Fractions

1. Free Nitrogen

- Too difficult (for me ;-))

2. Precipitation hardening

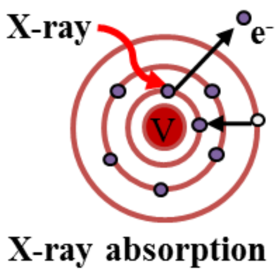
- Theoretically by measuring volume and average radius of the precipitates for the mean distance between particles

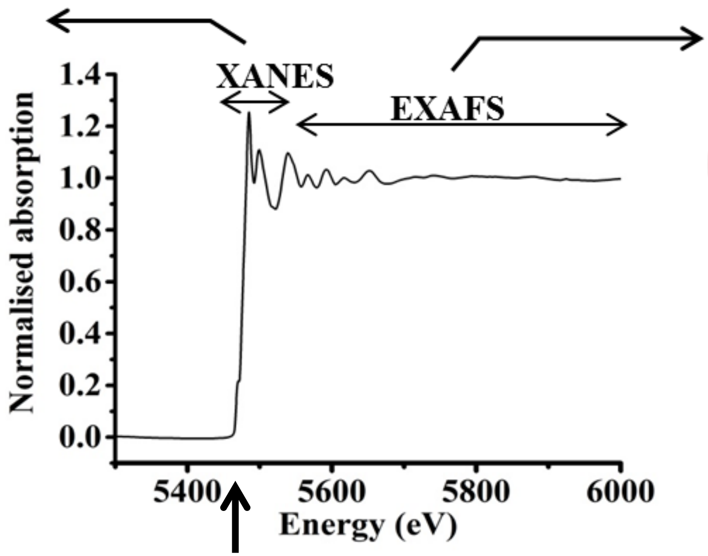
$$\Delta YS_{p,Orowan-Ashby} = \frac{0.8MGb}{2\pi\sqrt{1-\nu}L_{VC}} \ln\left(\frac{x}{2b}\right)\ (MPa)$$

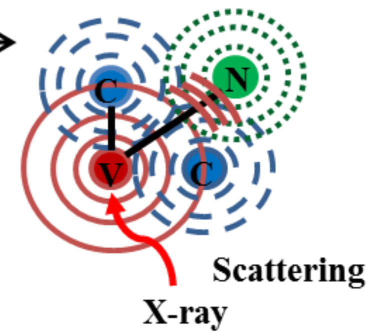
$$L_{VC} = \sqrt{\frac{2}{3}}\left(\sqrt{\frac{\pi}{f}} - 2\right) * r_{VC}\ (m)$$

Calculation of Precipitates Fraction vs. Dissolved Fraction

Synchrotron XAS for the Precipitation Fraction







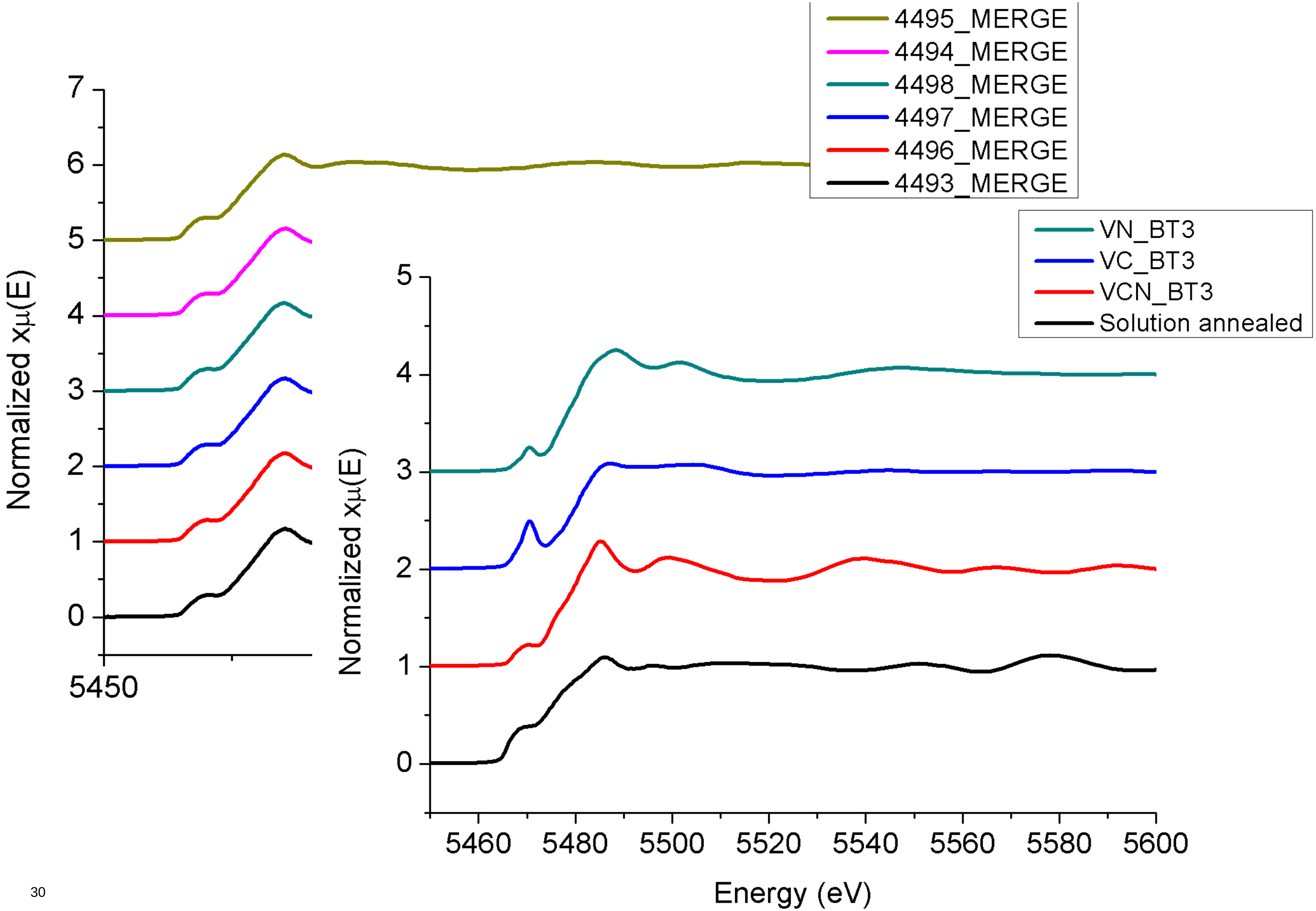
Absorption Edge by Photoelectric Absorption **– XANES - defines central atom type**

5465 eV for K-shell binding energy in V

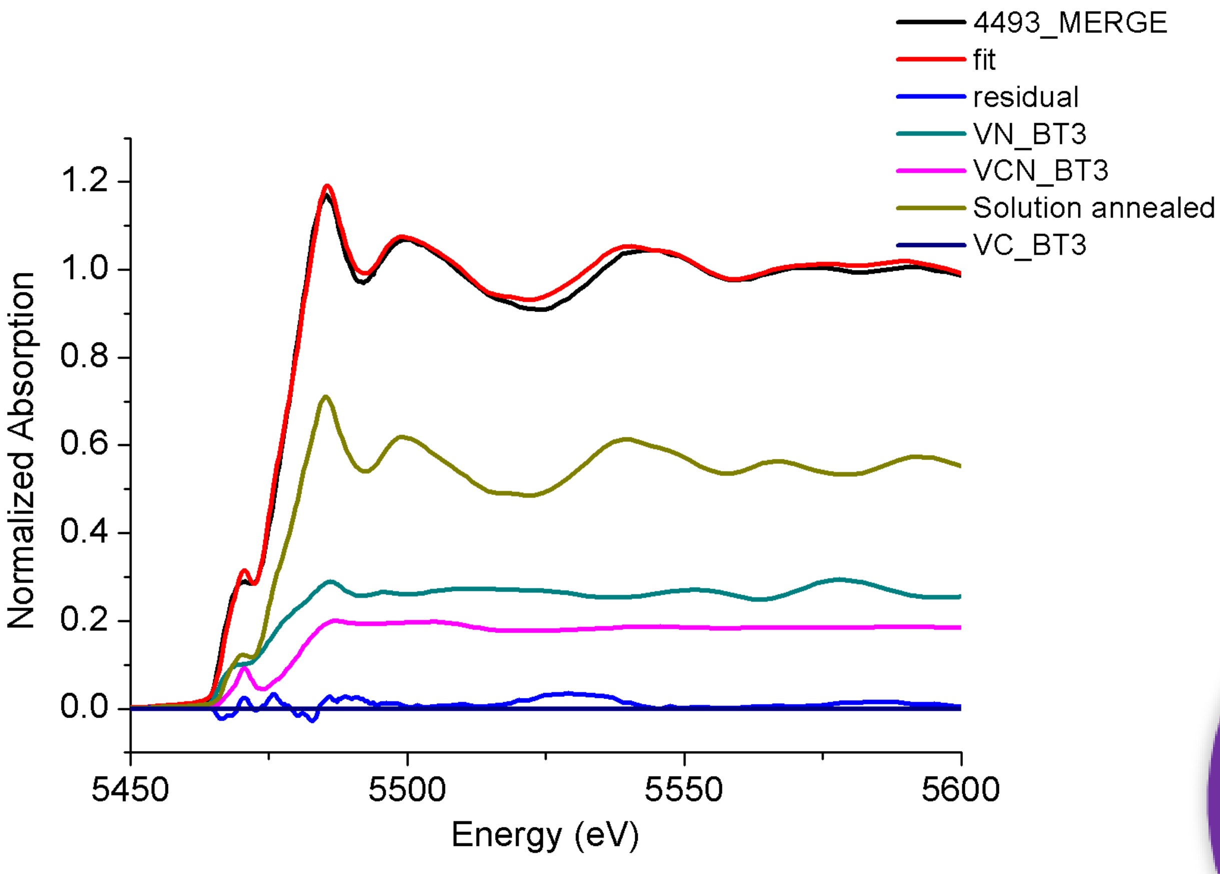
Interference between Emitted Photoelectron and Scattered X-Ray **from Surrounding Atoms – EXAFS – defines type of surrounding atoms**

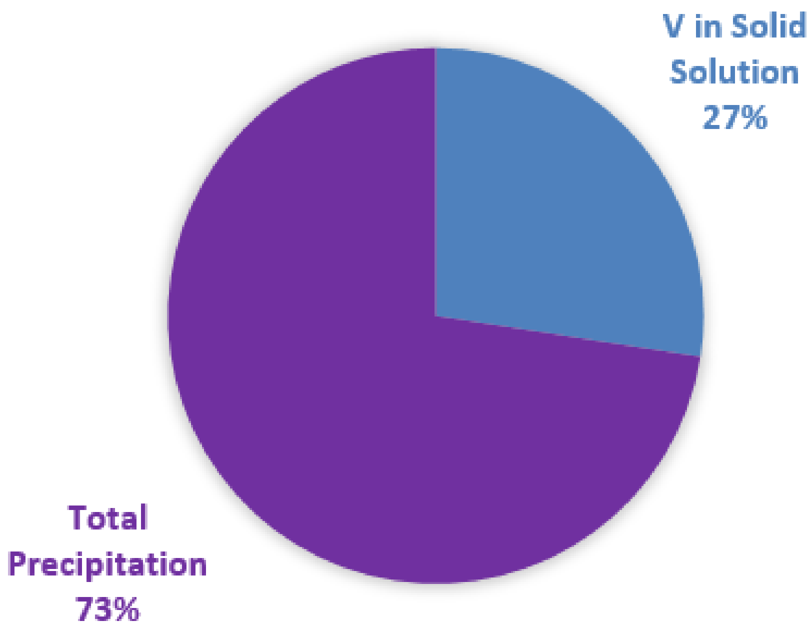
$$\chi(k) = \sum_{f} \frac{S_0^2 N_j}{k R_j^2} \left| f_j^{eff}(k, R_j) \right| \sin\left[2kR_j + \varphi_j(k)\right] e^{-2\sigma_j^2 k^2} e^{-\frac{R_j}{\lambda(k)}}$$

XAS Spectra on the Samples and Standard

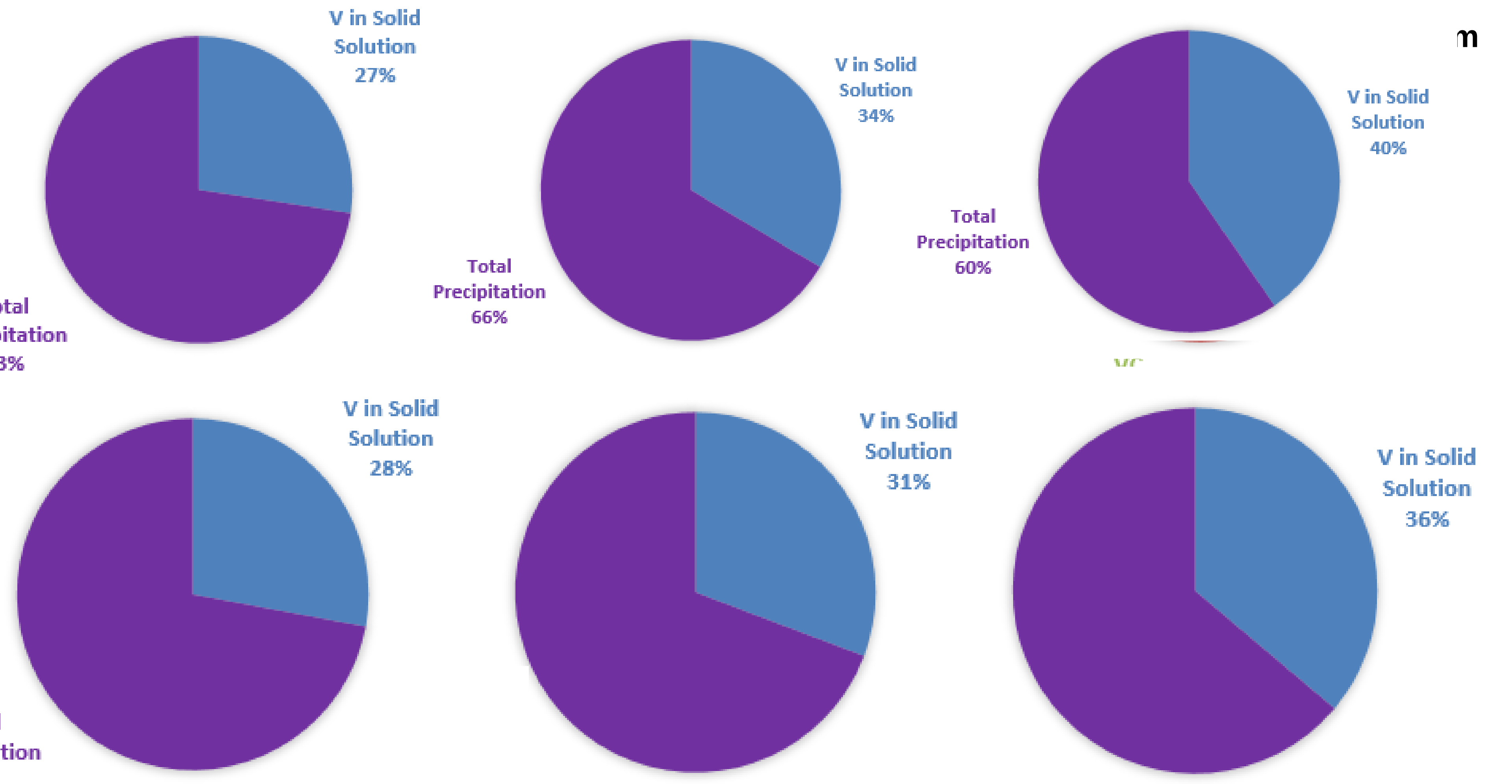


Calculation of Precipitates Fraction vs. Dissolved Fraction



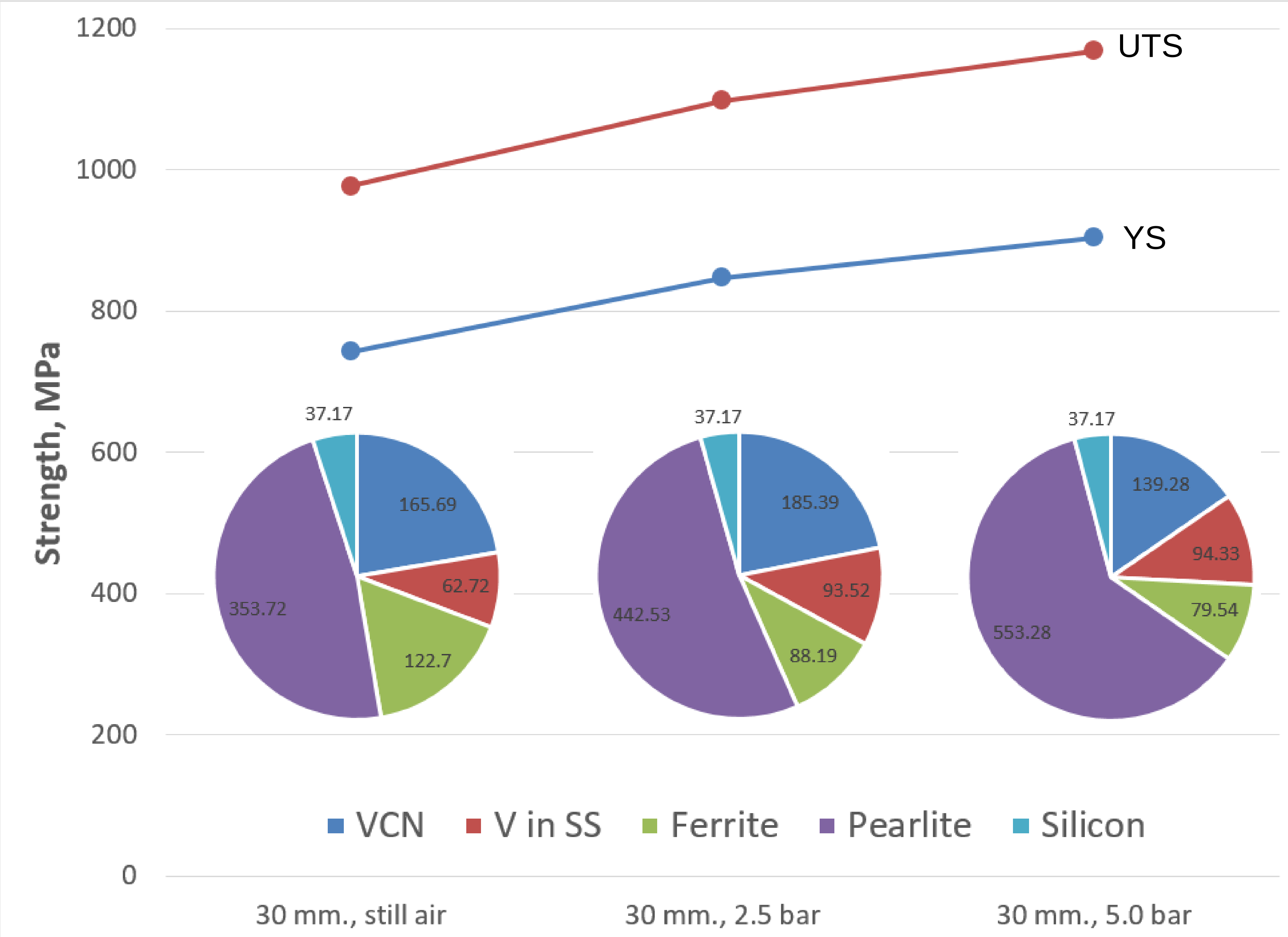


Results on XAS Fractions for All Samples



Hooray!!! All Terms can be Solved!!!

$$YS = f_{\alpha}\{35 + 58(\%Mn) + 17.4(D_{\alpha})^{-0.5}\} + (1 - f_{\alpha})\left\{178 + 3.8\left(\lambda_p\right)^{-0.5}\right\} + 63(\%Si) + 425(\%N)^{-0.5} + \Delta YS_p$$



1200
1000
800
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0
Strength, MPa
UTS
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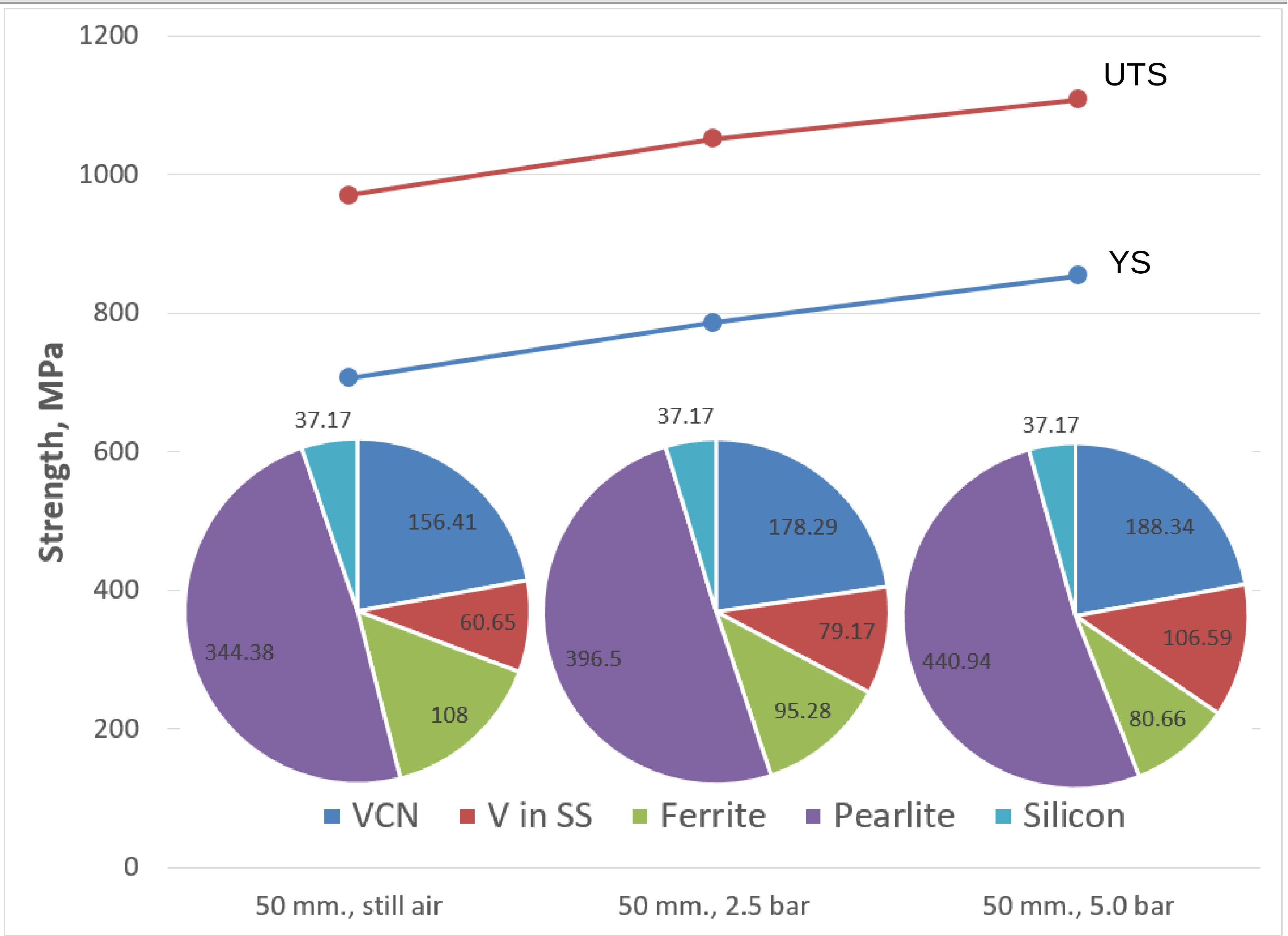

1200
1000
800
600
400
200
0
Strength, MPa
UTS
YS
37.17
156.41
60.65
108
344.38
37.17
178.29
79.17
95.28
396.5
37.17
188.34
106.59
80.66
440.94
VCN
V in SS
Ferrite
Pearlite
Silicon
50 mm., still air
50 mm., 2.5 bar
50 mm., 5.0 bar

Conclusions

- Forged Components can be Forged and Air Cooled Without Heat Treatment
- Extra Ordinary Strength from Conventional Composition, mainly from Pearlite
- Process Window for Different Bar Sizes can be Determined
- 27-40% of Vanadium is still in the Solid Solution
- At Highest Cooling Rate (Highest Air Pressure), Lowest Fraction Contributed by Precipitation Hardening
- 6 The Methodology can be Followed in the Industry – Both Production and R&D

Acknowledgement