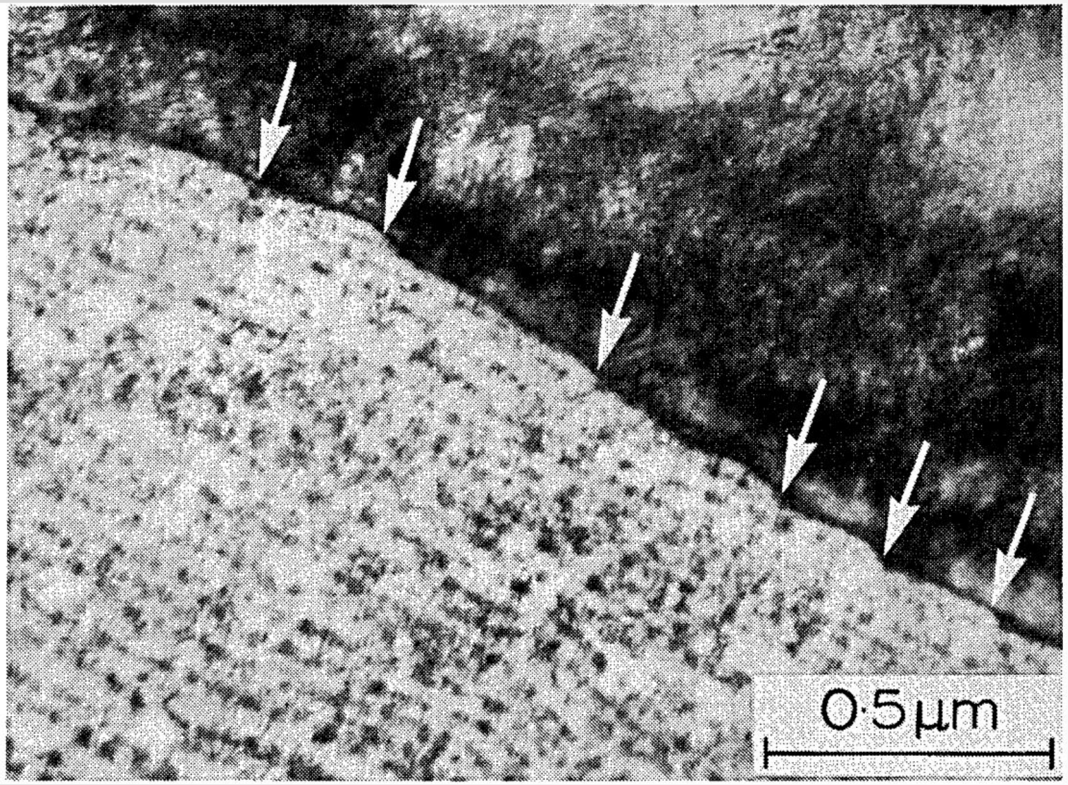
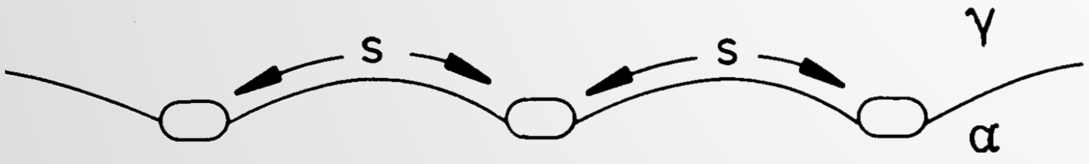
The interaction between moving α/γ interface and interface precipitation carbides during the cyclic phase transformations in low alloy steels

Haokai Dong, Chi Zhang, Hao Chen, Zhigang Yang

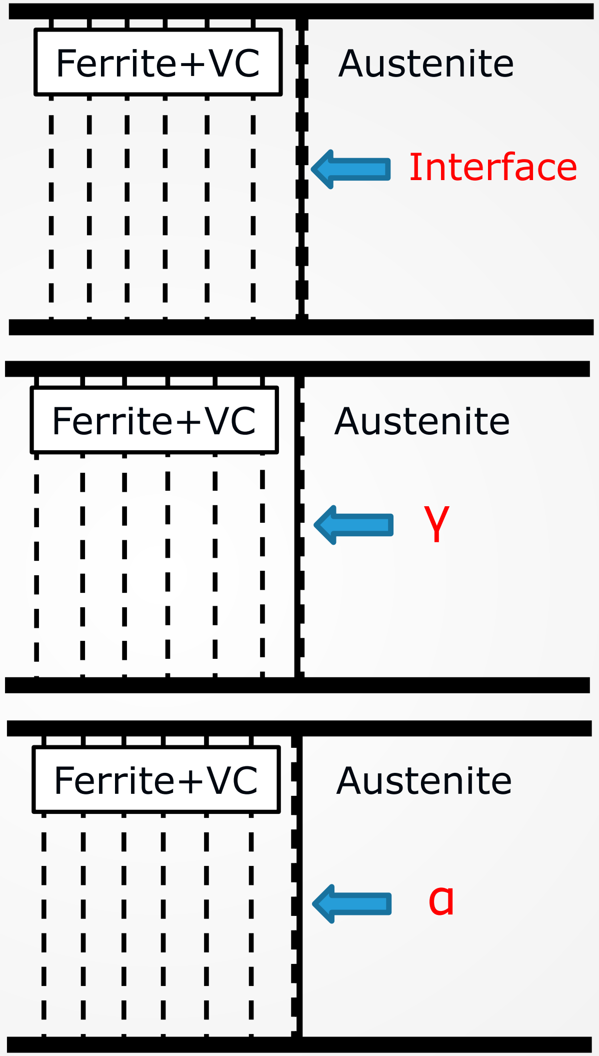
School of Materials Science and Engineering
Tsinghua University, Beijing, China

Introduction





Ricks R A, Howell P R. Metal Science, 1982



- Large PF Branch:

Chen M Y et al, Acta. Mater, 2014

Liu W J, Metall. Trans. A, 1993

$\Delta G_p^{\max} = \sim 260\ J/mol$

Precipitation Modes

- Small PF Branch:

T Murakami, ISIJ International, 2012

1nm VC, $\Delta G_p = \sim 6\ J/mol$

Interaction Force (Pinning Force)

$P_z = \frac{3f\sigma}{2}$ Rigid Boundary Model

Divided into Two Branches

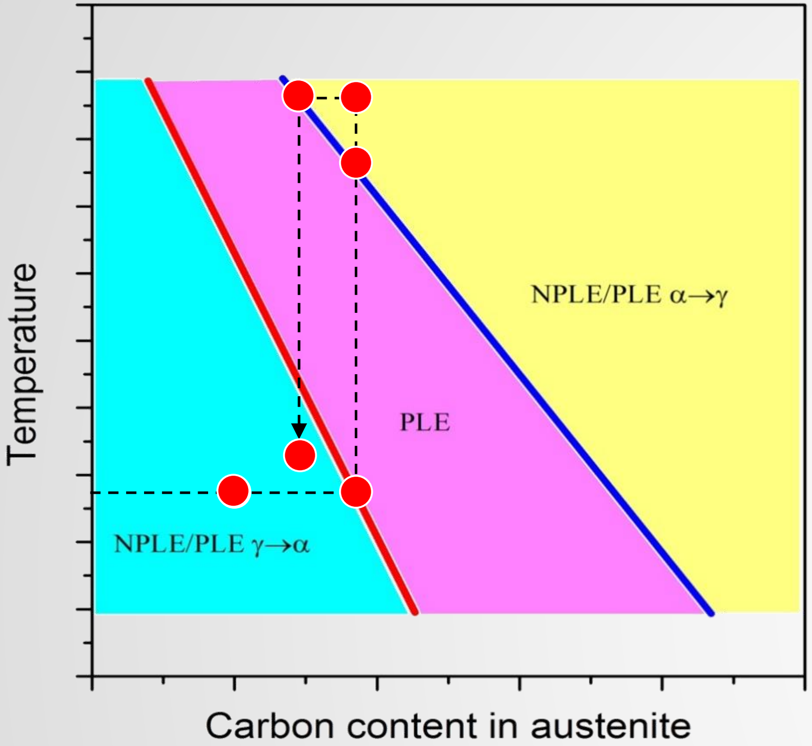
S … 013

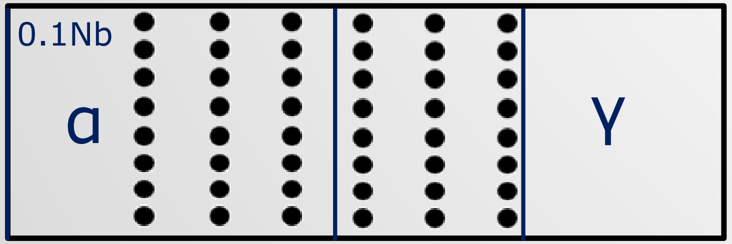
3DAP, nano-clusters, low σ

Still Controversial !

How to quantitatively determine the PF ?

Experiment Design



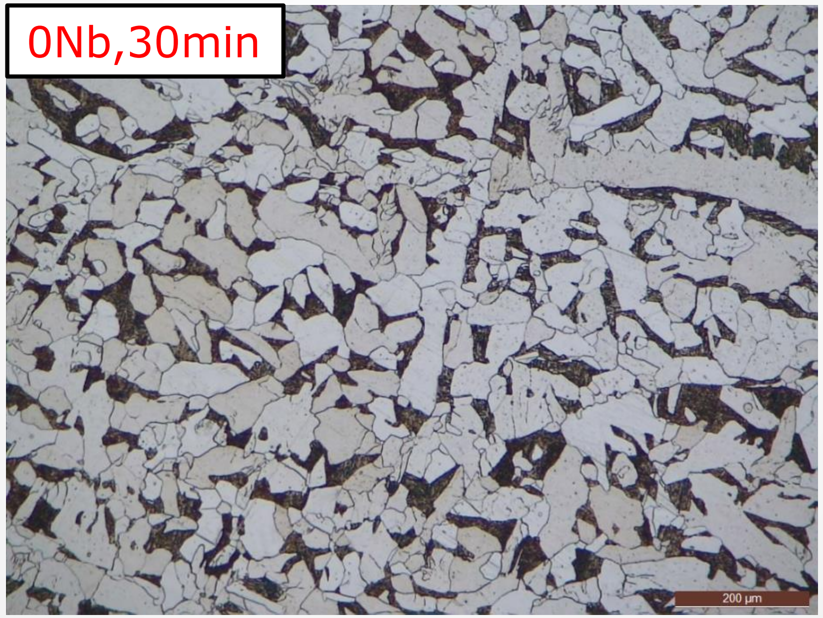


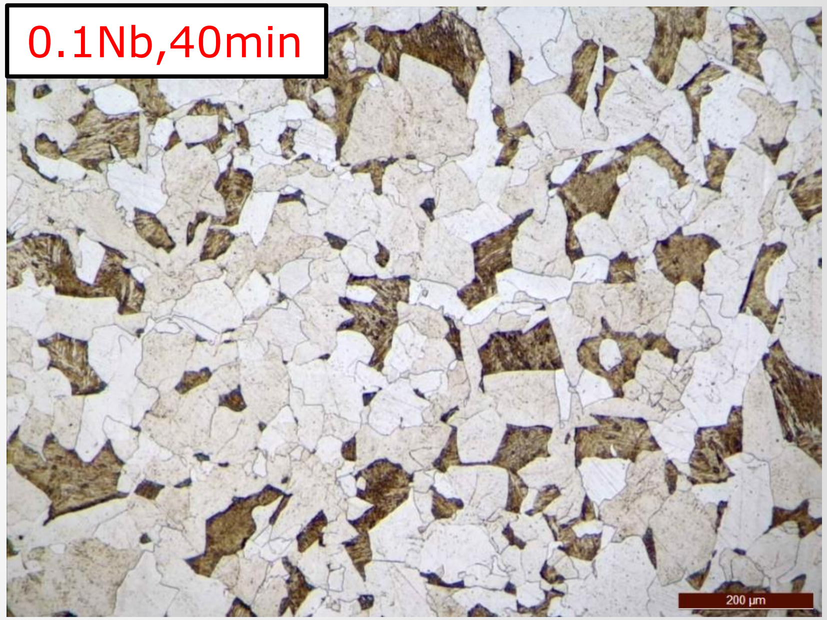
- Chemical composition:

Alloy	Composition, mass%				
	C	Si	Mn	Nb	Fe
0Nb	0.1	0.05	1.5	—	Bal.
0.1Nb	0.08	0.05	1.5	0.1	Bal.

Vickers Hardness:
0Nb: 118.1±2.2HV
0.1Nb: 136.8±9.1HV

- OM (Isothermal holding at 700℃):





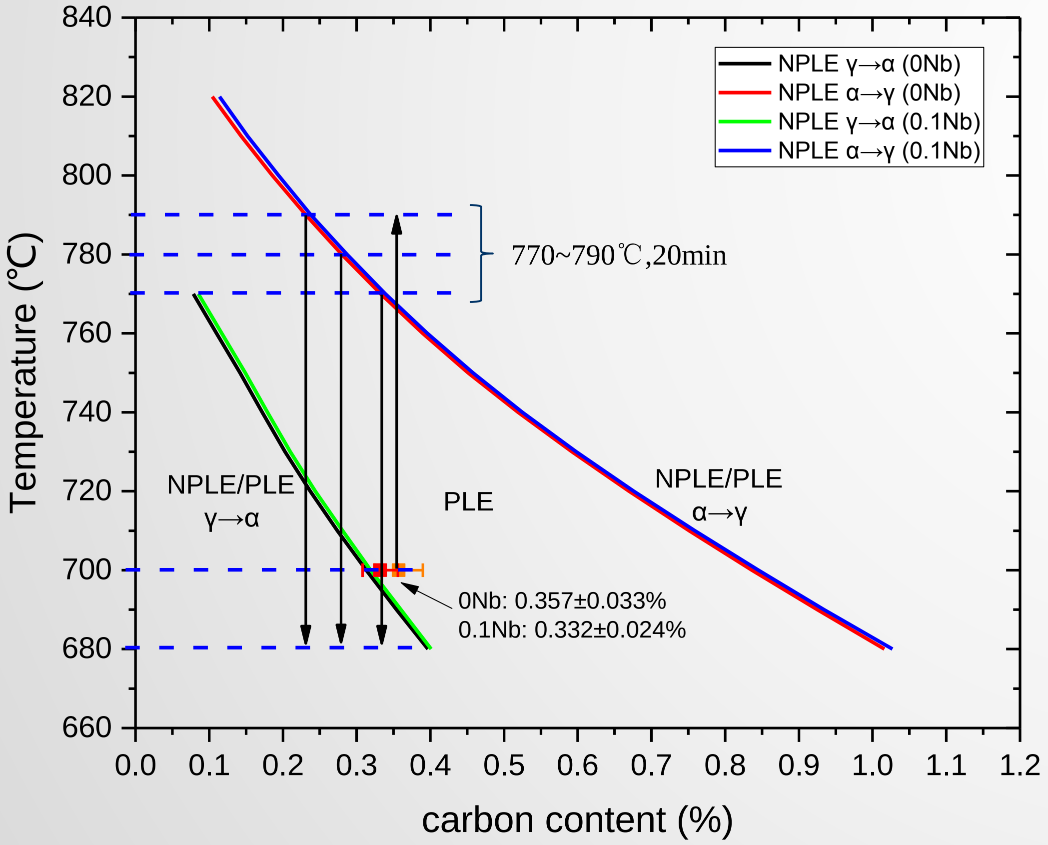
Volume fraction of ferrite
- 0Nb: 72.05±2.37%→ Lever rule: 0.357±0.033%
- 0.1Nb: 76.85±1.77% → Lever rule: 0.332±0.024%

Experiment Design

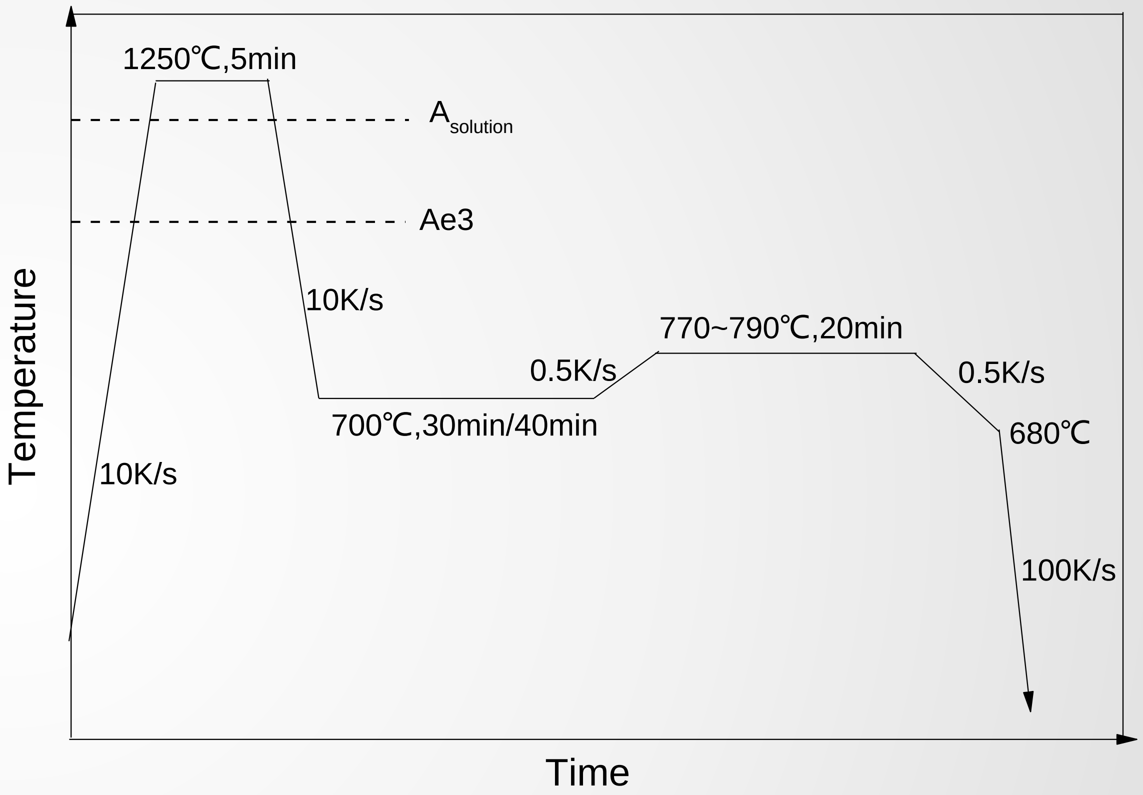
- Chemical composition:

Alloy	Composition, mass%				
	C	Si	Mn	Nb	Fe
0Nb	0.1	0.05	1.5	—	Bal.
0.1Nb	0.08	0.05	1.5	0.1	Bal.

- PLE/NPLE line:



- Heat Treatment:

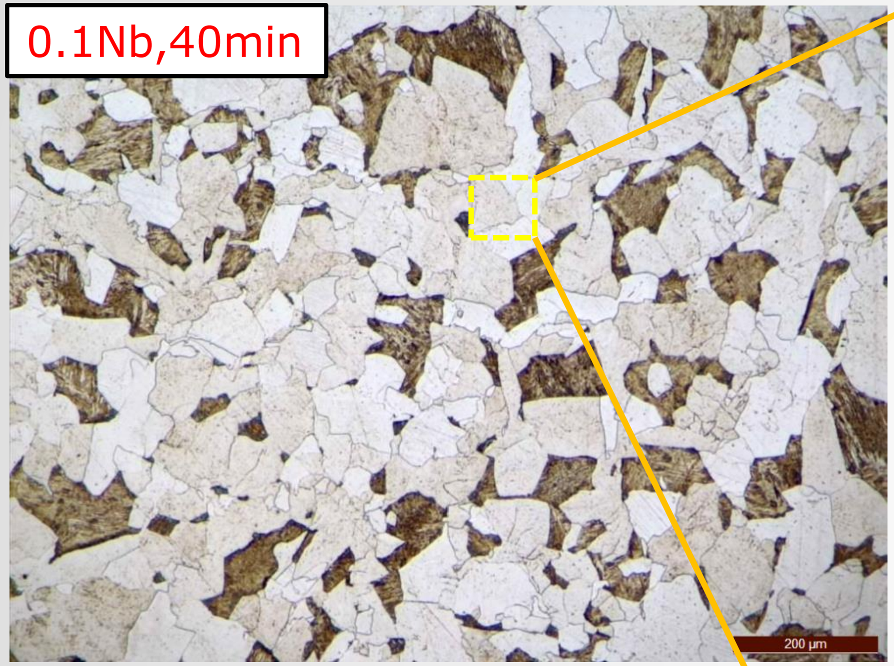


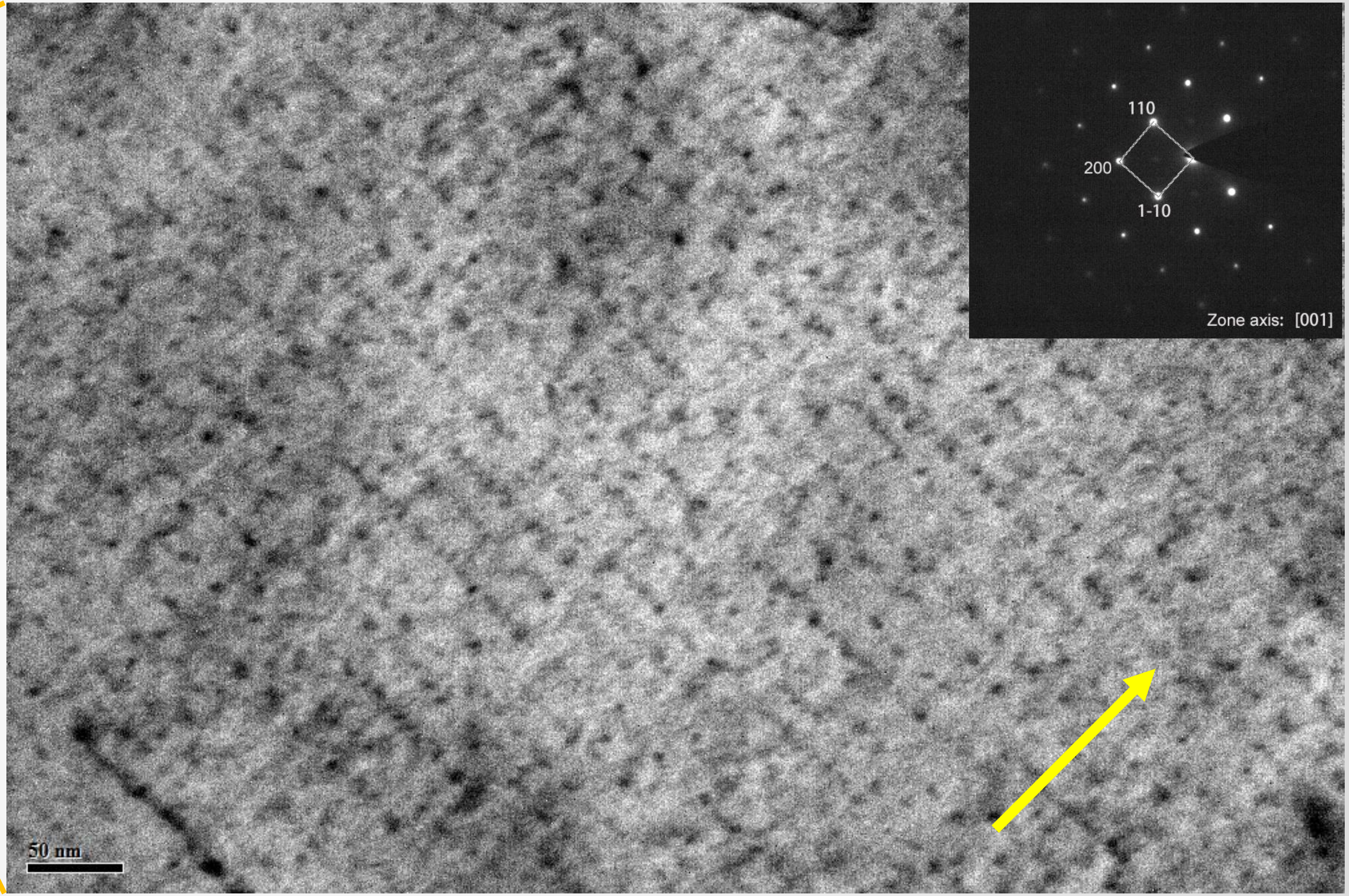
- Characterization Method

- ☐ Optical Microscopy (OM)
- ☐ Dilatometry
- ☐ TEM

Experimental Results: TEM Characterization

- Isothermally hold at 700 ℃ for 40min, 0.1Nb





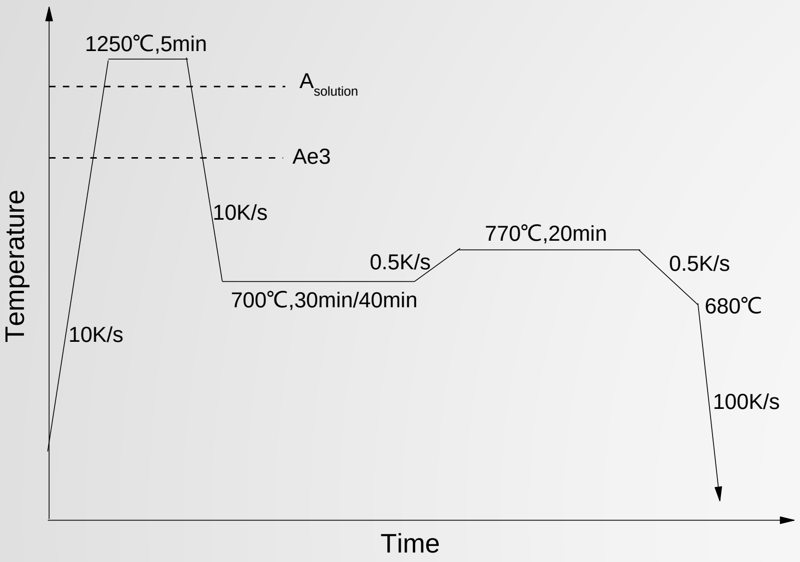
Plane of interphase precipitation: ~(-110)

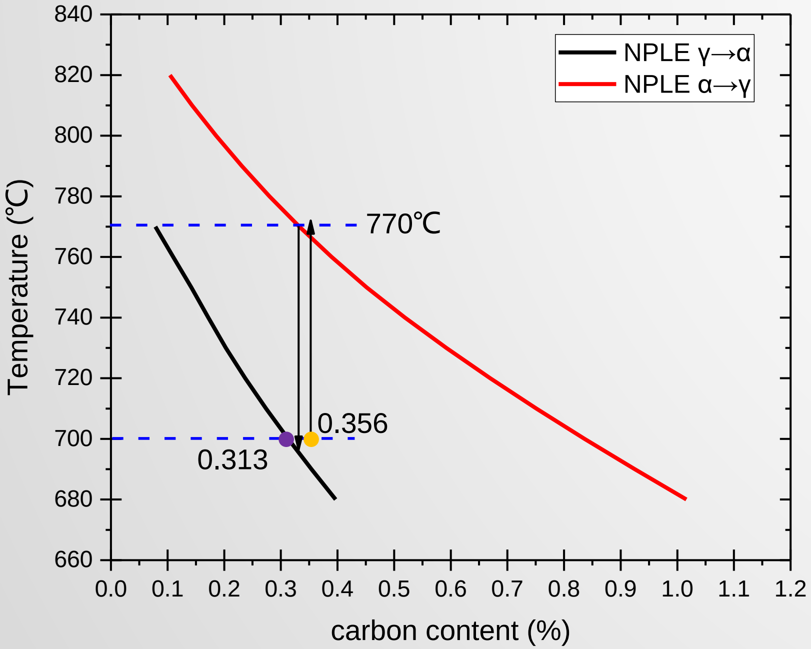
Inter-sheet spacing: 18~22nm

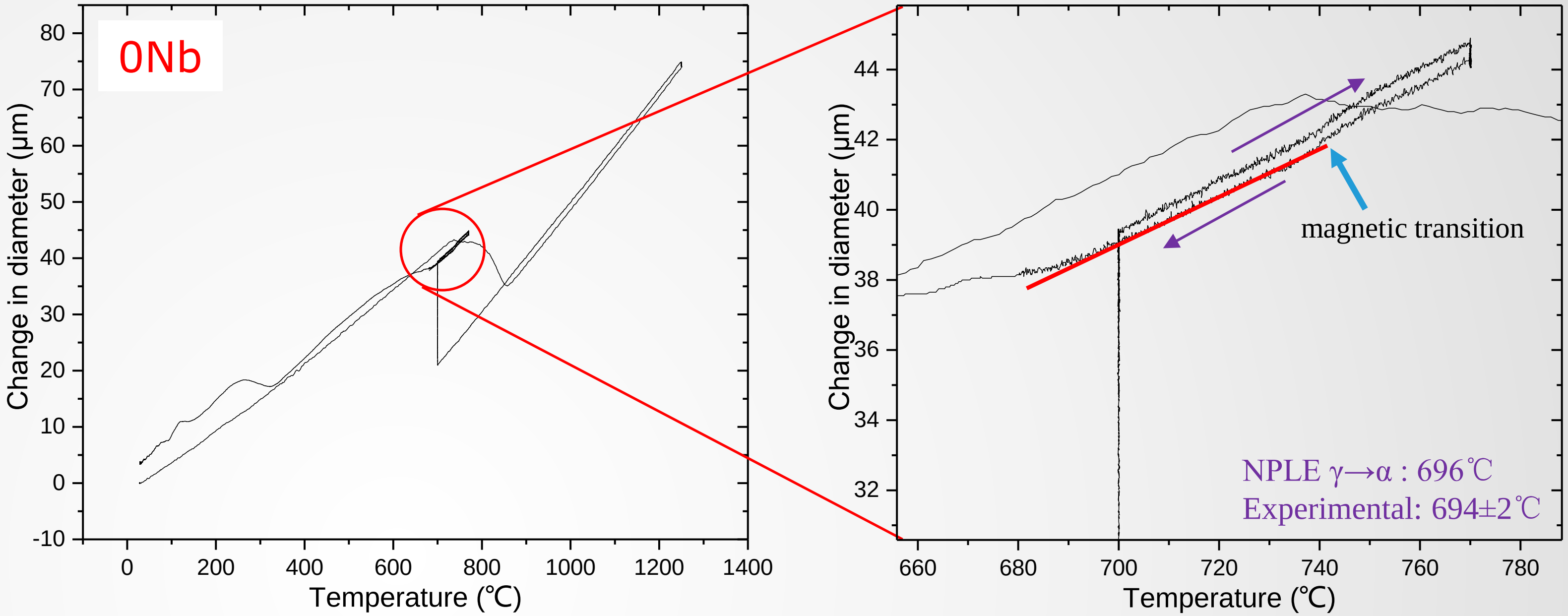
Size of NbC carbides: 5-7nm

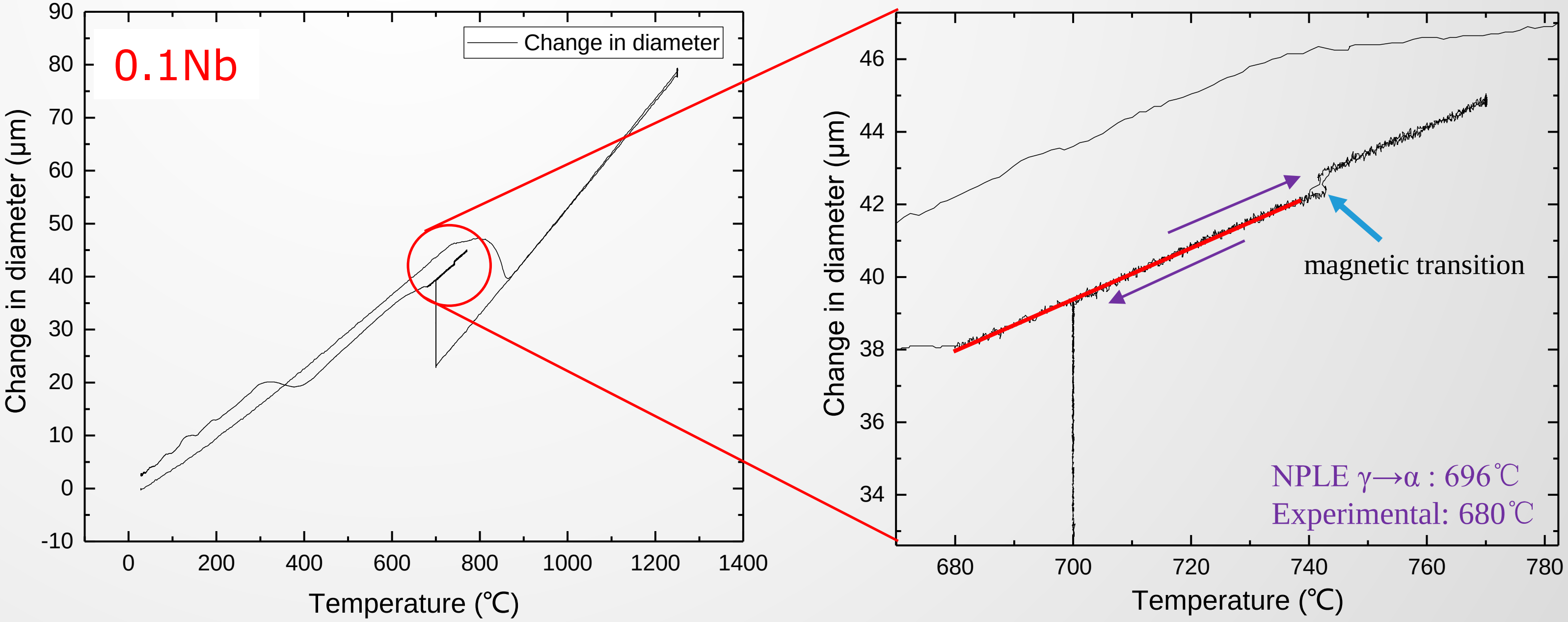
Experimental Results: Dilatometry

- Single Cyclic Transformation at 770℃



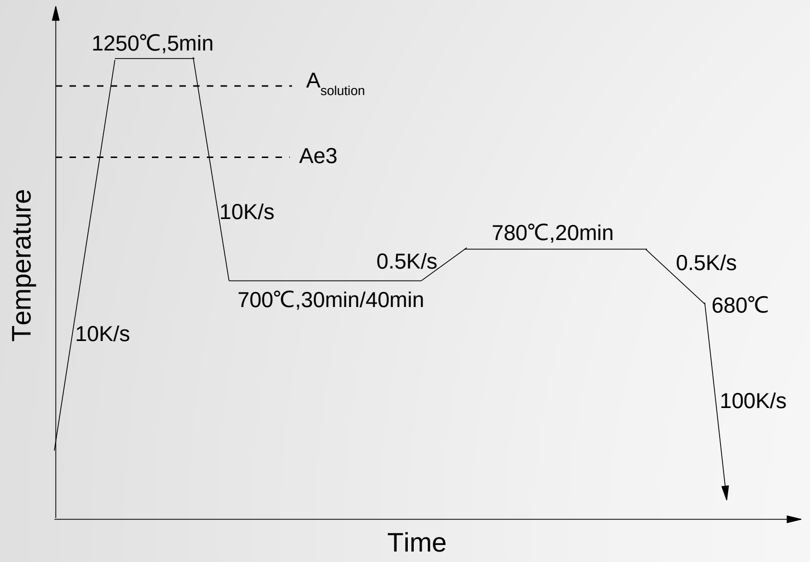


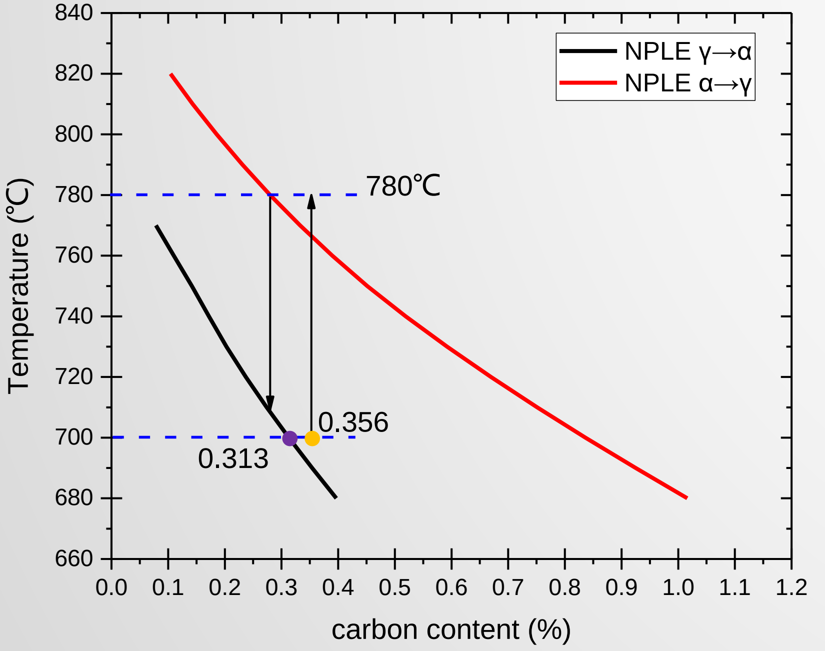


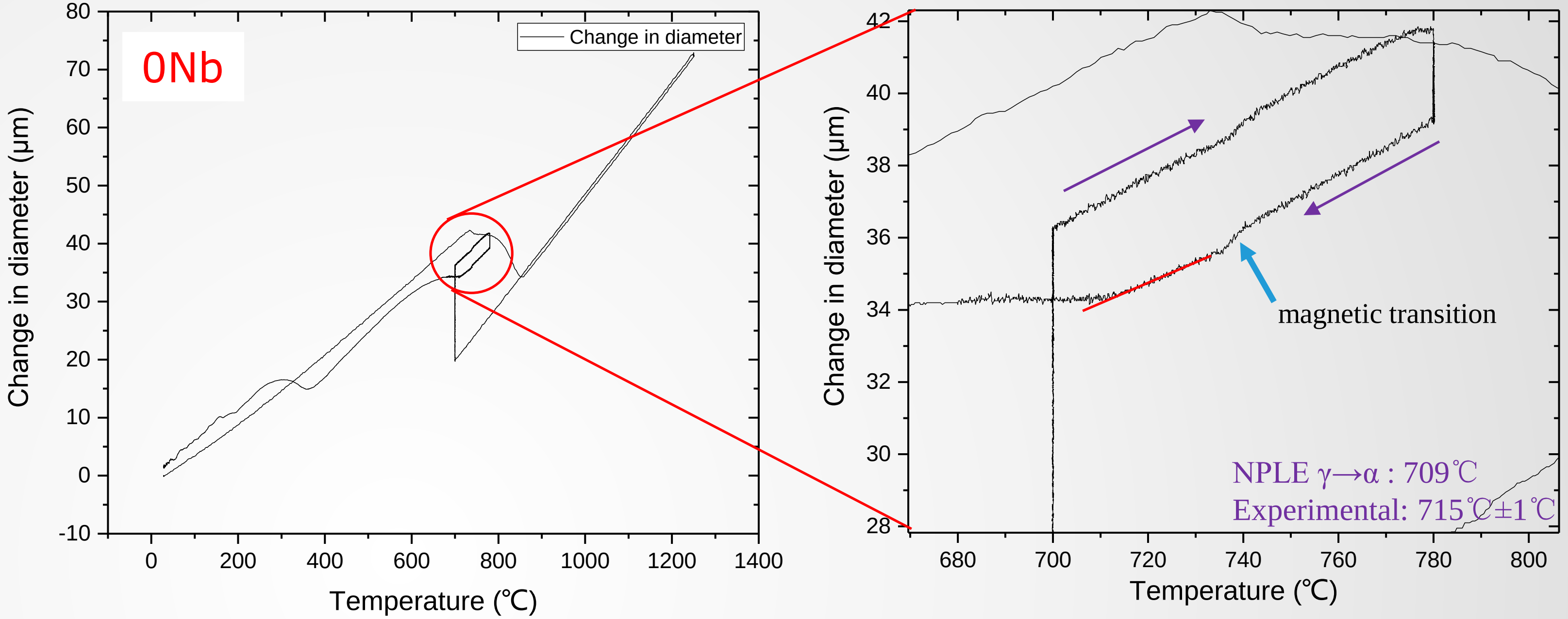


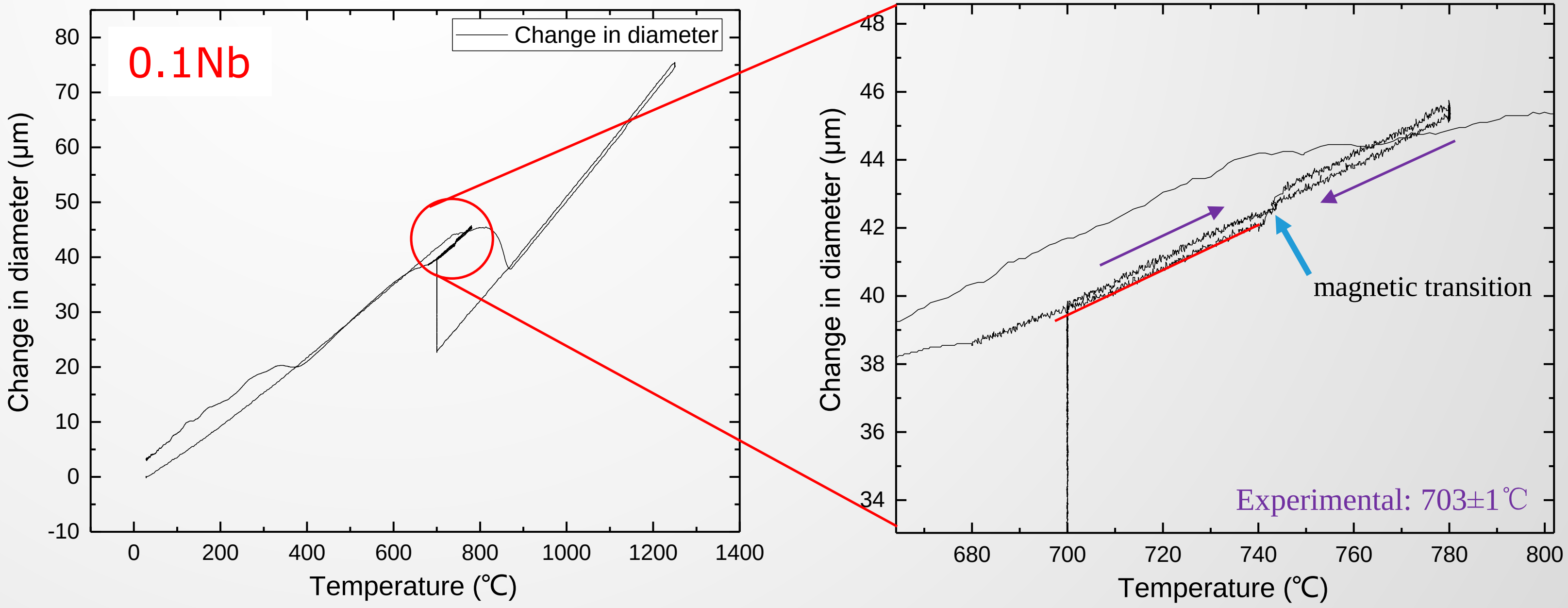
Experimental Results: Dilatometry

- Single Cyclic Transformation at 780℃



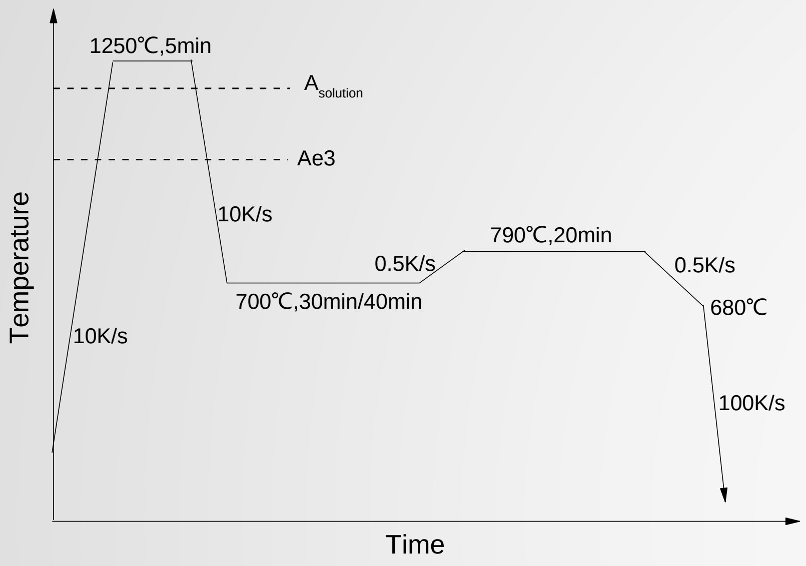


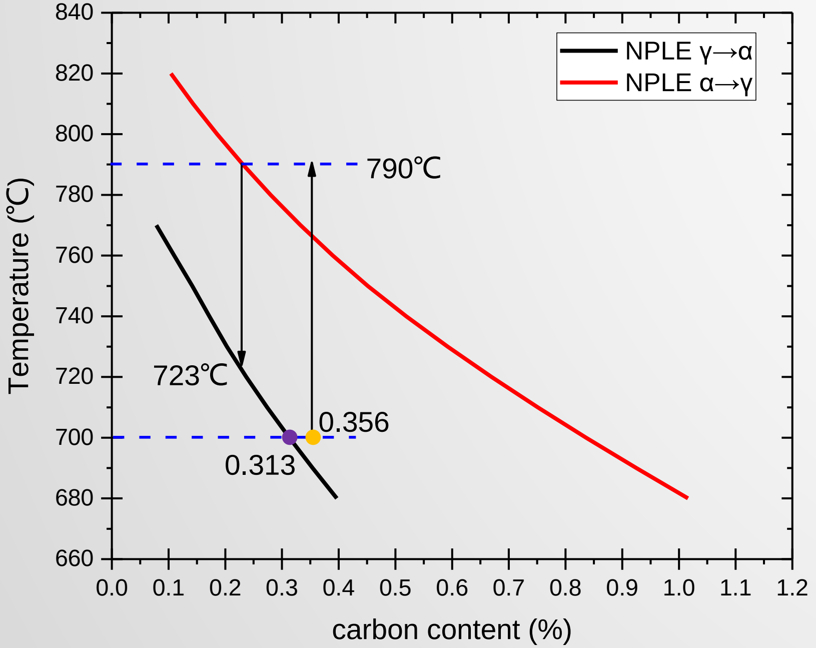


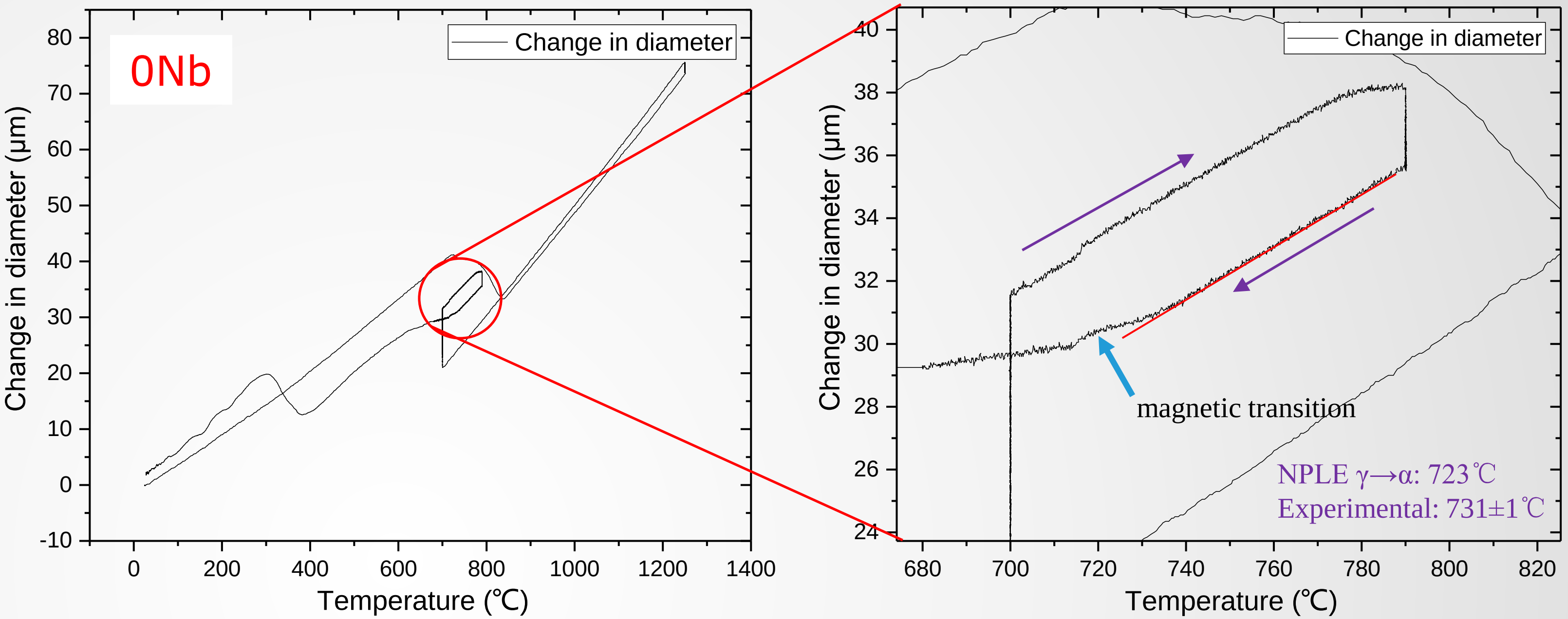


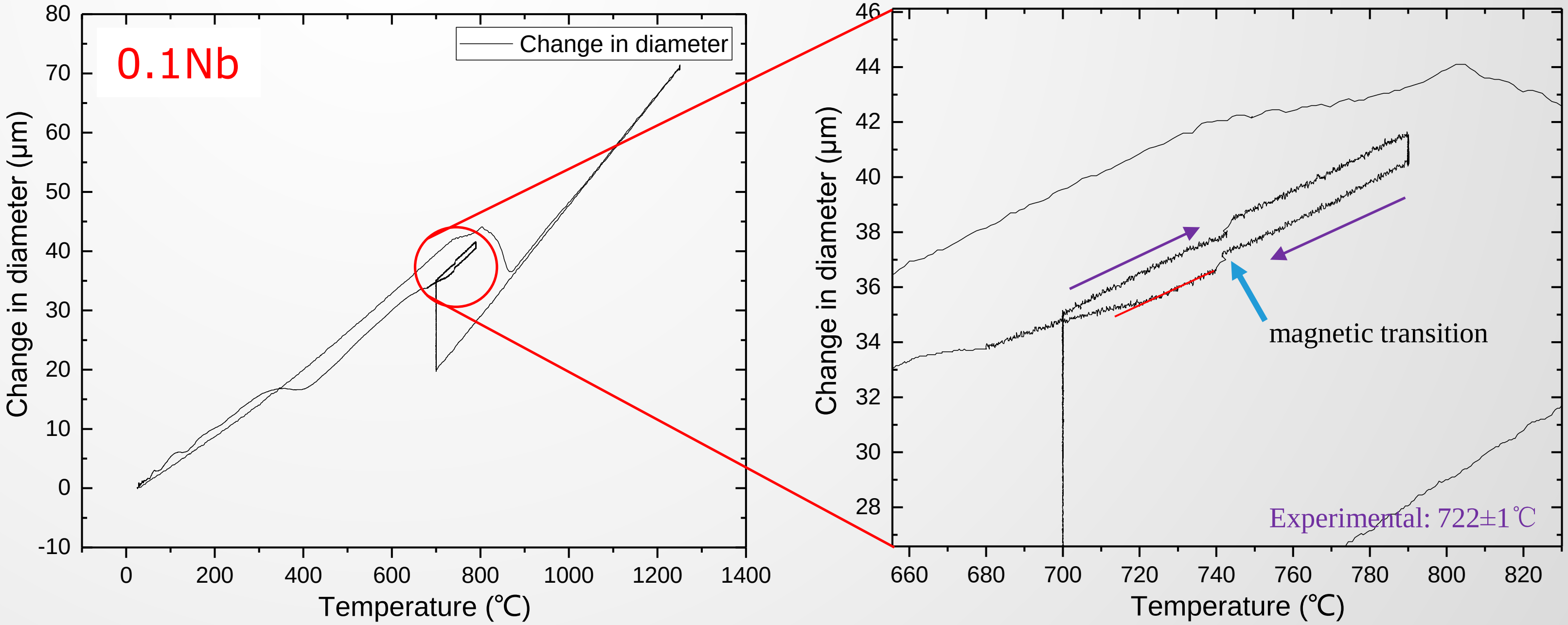
Experimental Results: Dilatometry

- Single Cyclic Transformation at 790℃



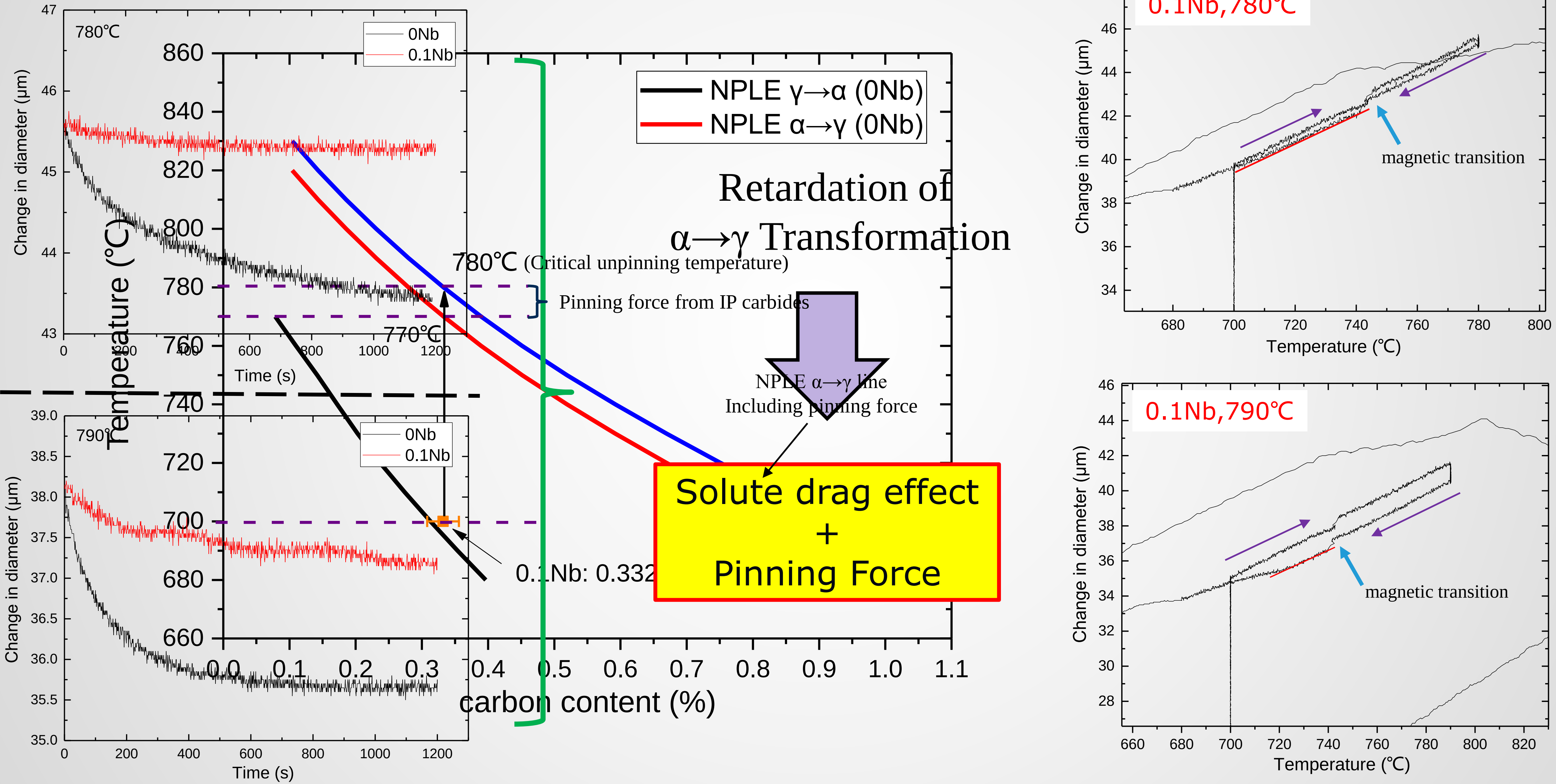






Experimental Results: Kinetics of α→γ Transformation

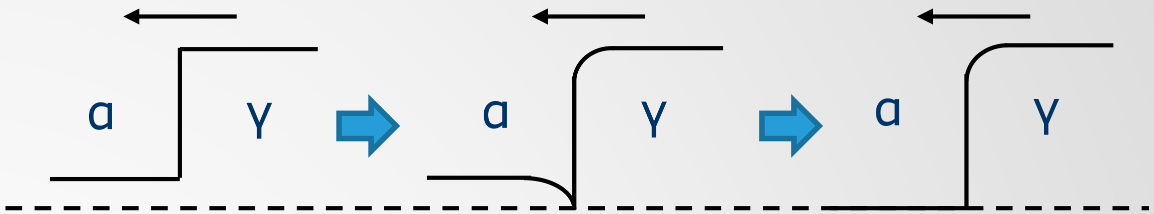
- Cyclic Transformation at 780 ℃ and 790℃



Discussion: Determination of Pinning Force

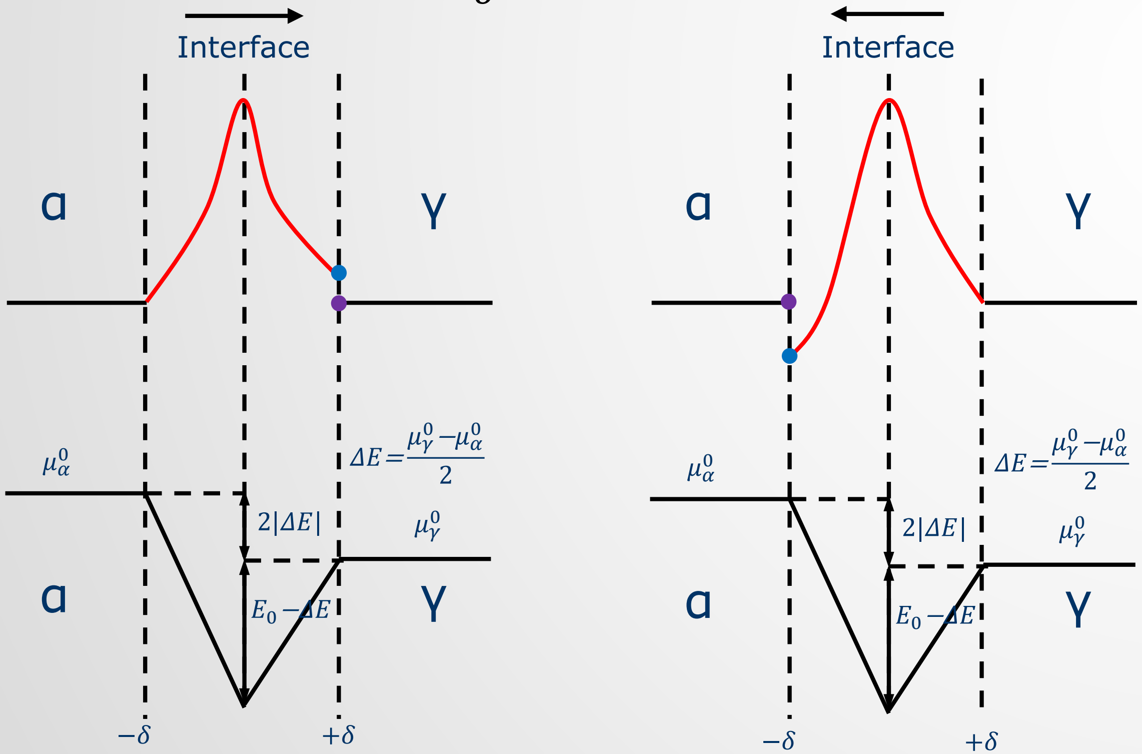
- The chemical driving force for α→γ transformation:

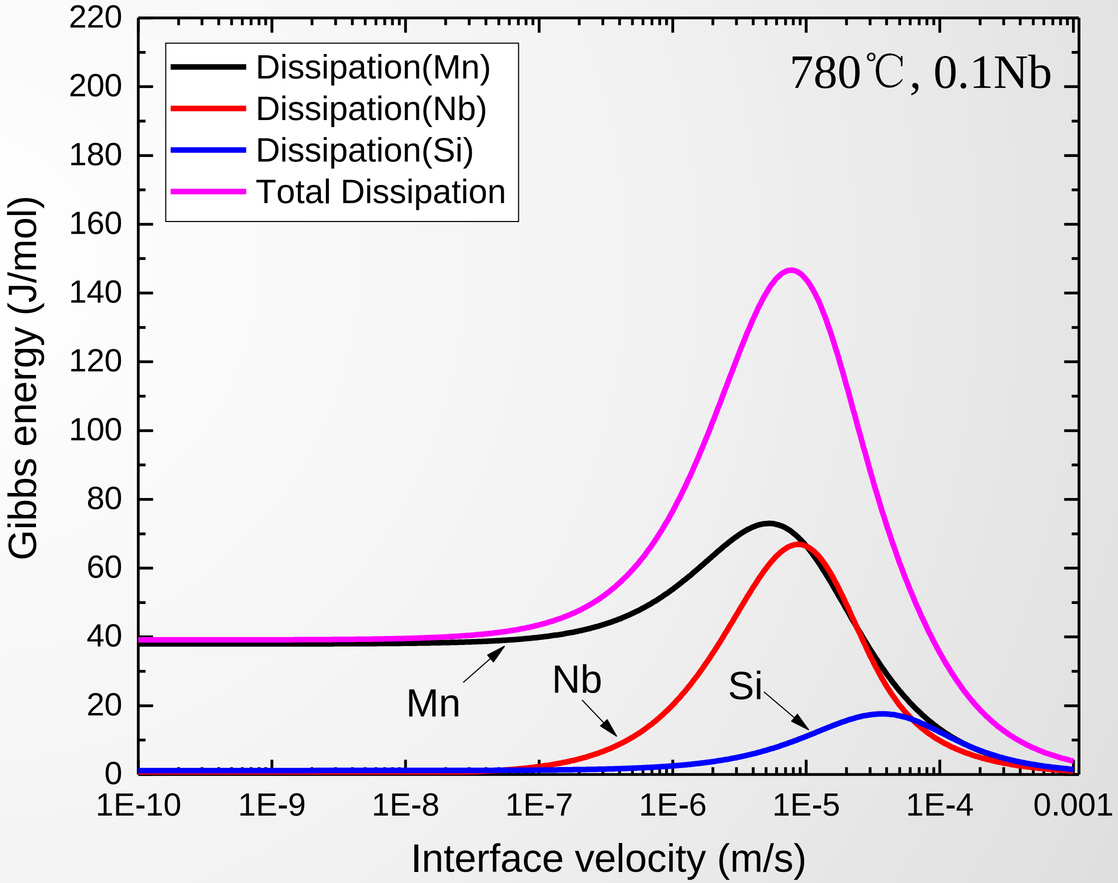
$$\Delta G_m^{chem} = \sum_i^n x_i^0 \left[\mu_i^{\alpha/\gamma}\left(x_i^{\alpha/\gamma}\right) - \mu_i^{\gamma/\alpha}\left(x_i^{\gamma/\alpha}\right)\right]$$



- The dissipation of Gibbs energy due to solute drag effect:

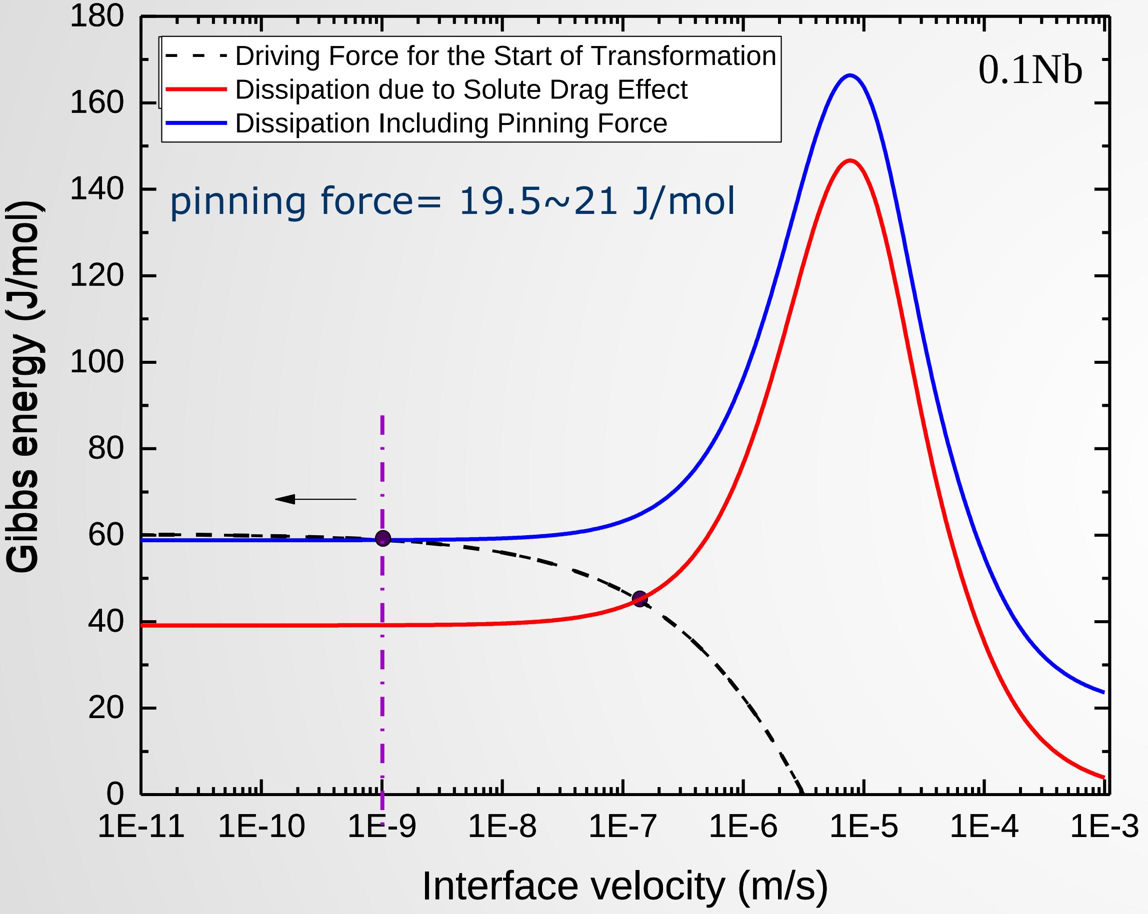
$$\Delta G_m^{diff} = -\int_{-\delta}^{+\delta} (X - X_0)\left(\frac{dE}{dx}\right) dx$$

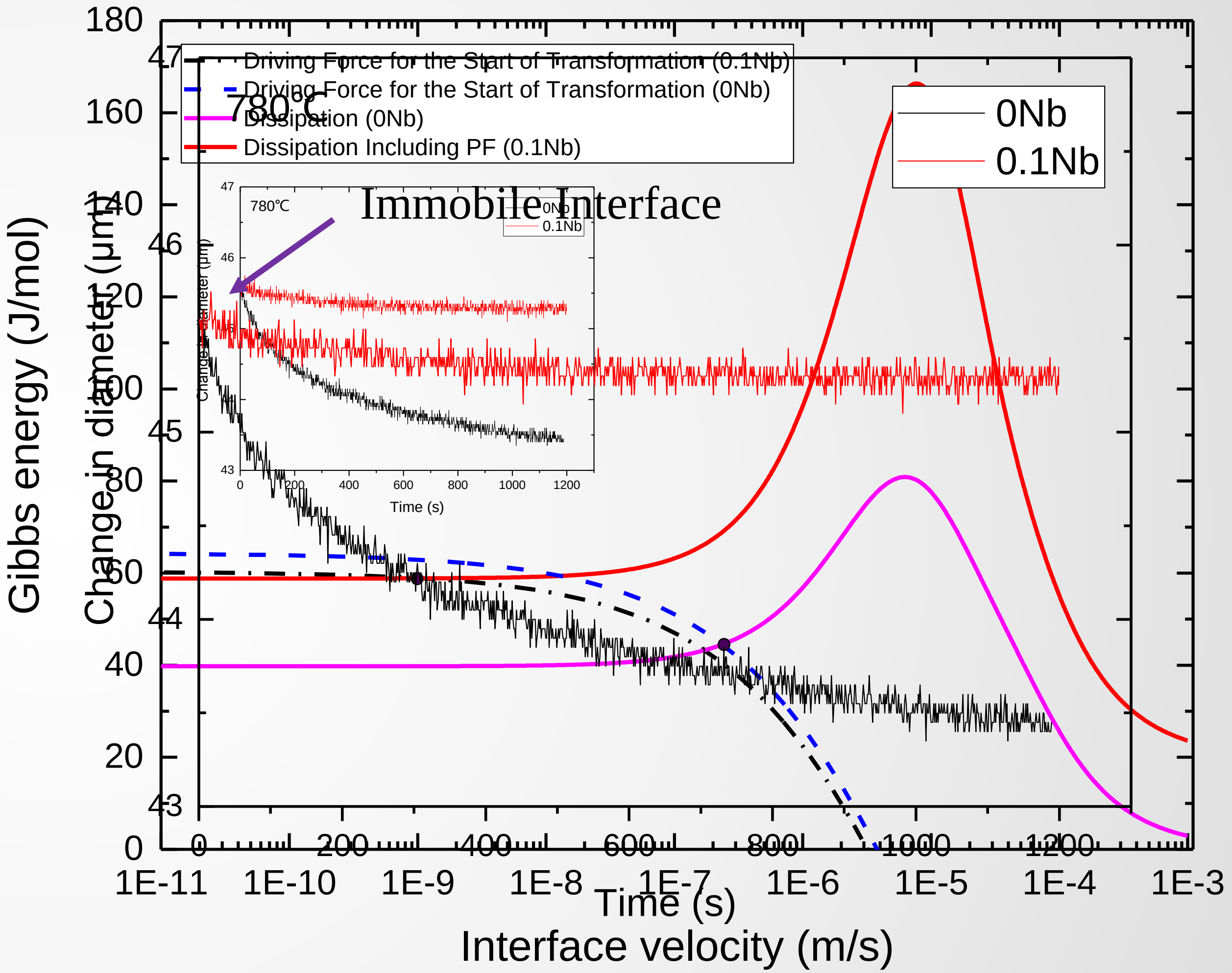




Discussion: Determination of Pinning Force

- Analysis of PF for 780℃ Cyclic Phase Transformation





Interface velocity at initial stage: 1.35e-7 m/s

The velocity of immobile interface: ≤ 1e-9 m/s

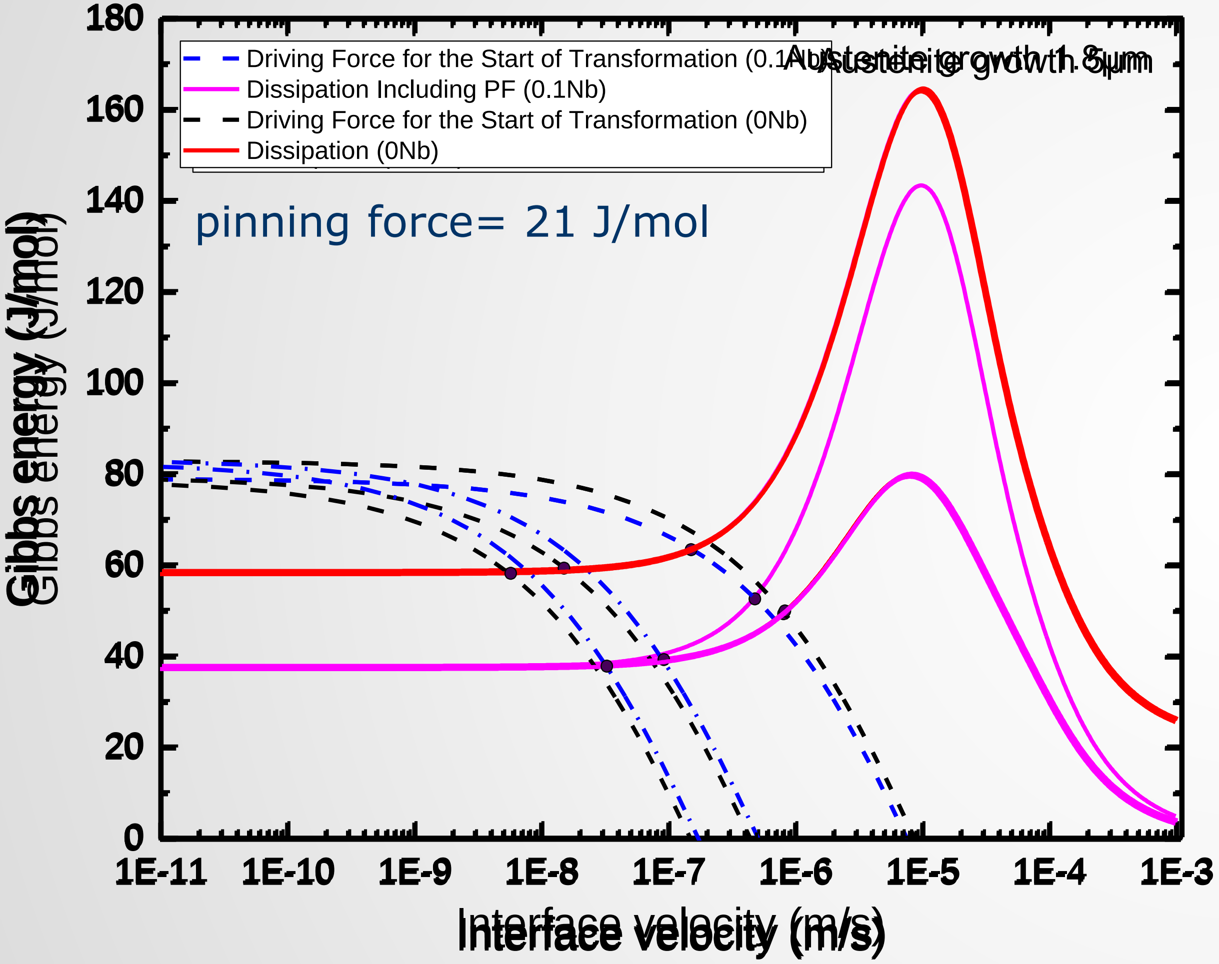
Pinning Force is existent !

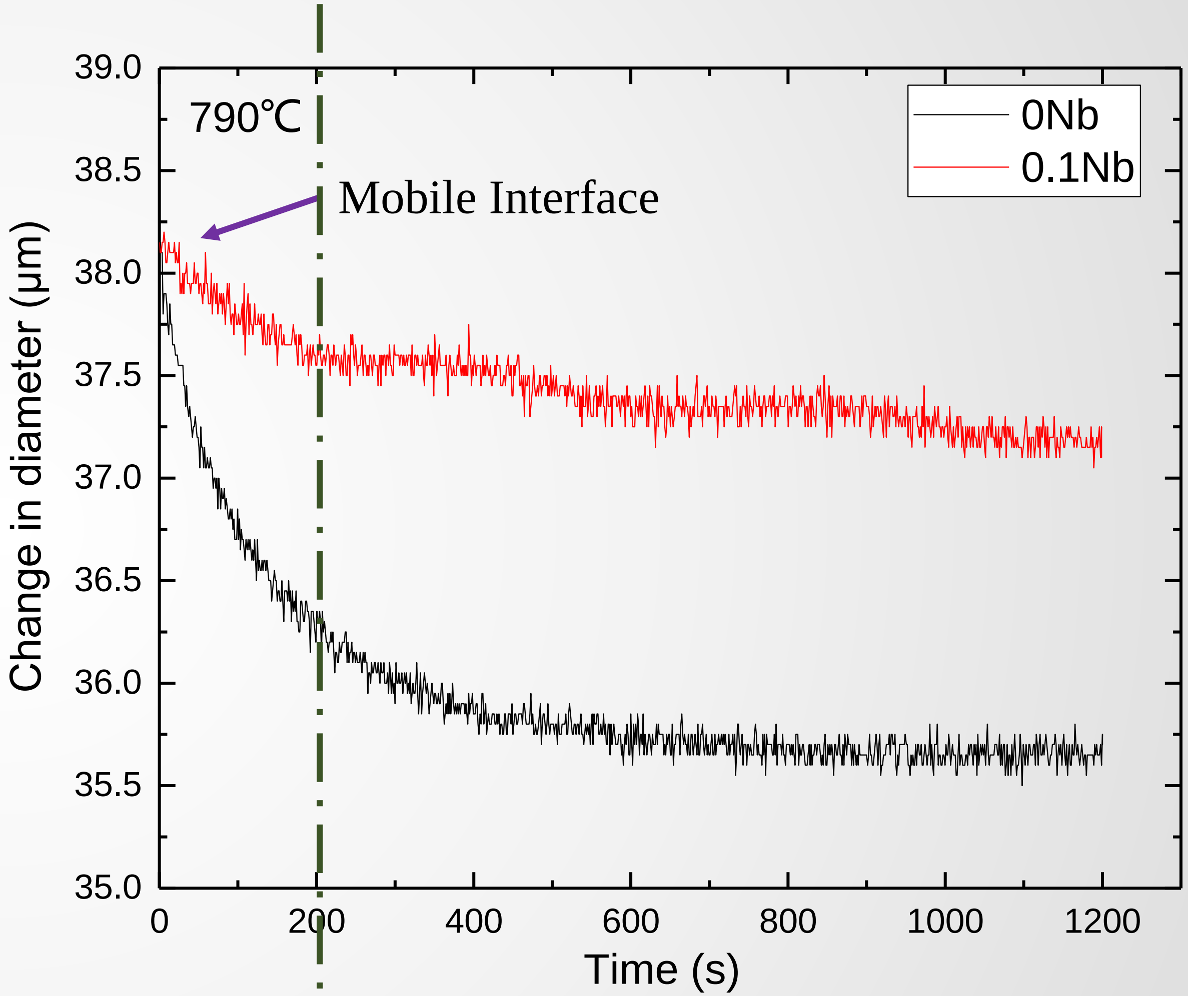
Vs (0Nb): 2.4e-7 m/s

Vs (0.1Nb): 1e-9 m/s

Discussion: Determination of Pinning Force

➤ Analysis of PF for 790℃ Cyclic Phase Transformation





Vs (0Nb): 8.3e-7 m/s

Vs (0.1Nb): 4.8e-7 m/s

+ Pinning Force

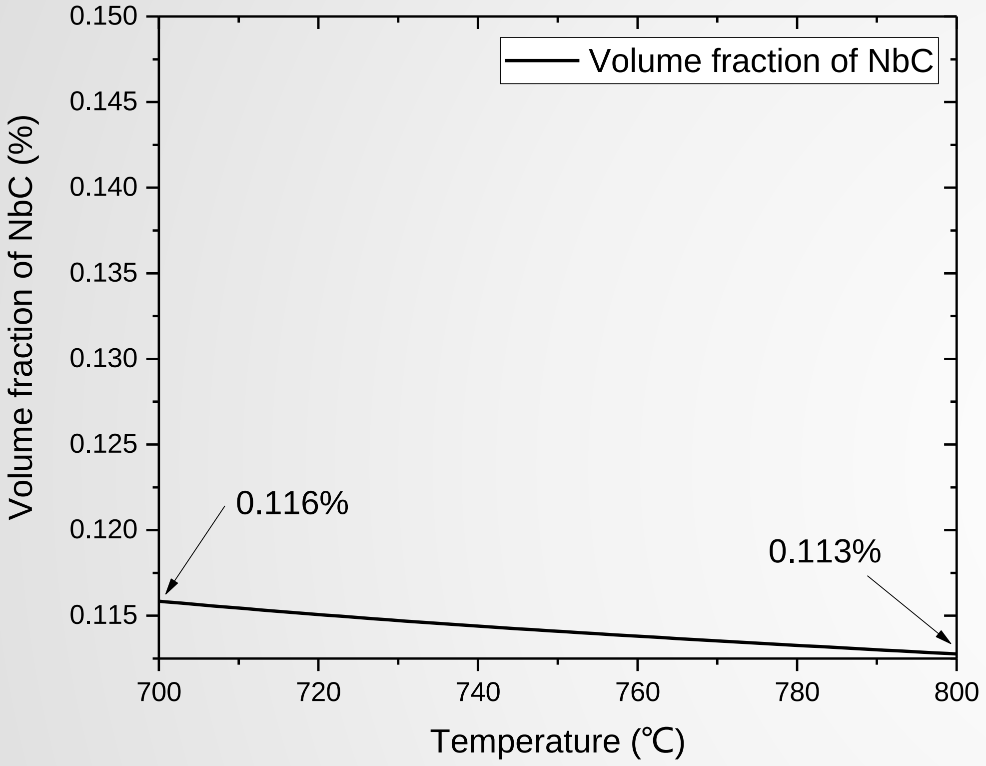
Vs (0Nb): 8.3e-7 m/s

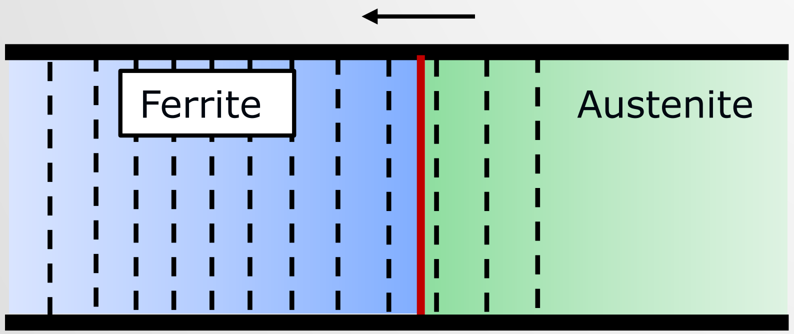
Vs (0.1Nb): 1.5e-7 m/s

Good qualitative agreement

Discussion: Carbide Dissolution

- ThermoCalc calculation for volume fraction of NbC vs Temperature





$$\lg([Nb]\bullet[C])_{\alpha} = 5.43 - 10960/T$$ [2]

$$\lg([Nb]\bullet[C])_{\gamma} = 2.206 - 6746/T$$

[2]雍岐龙. 钢铁材料中的第二相. 北京：冶金工业出版社, 2006

- 700℃, The Solubility of NbC in Ferrite : $1.47\times10^{-6}\ \%^2$

  PE： $w_c^{\alpha} = 1.32\times10^{-2}\%$, $w_{Nb}^{\alpha} = 1.11\times10^{-4}\% \ll 0.1\%Nb$ (bulk)

- 790℃, The Solubility of NbC in Ferrite: $1.32\times10^{-5}\ \%^2$

  PE： $w_c^{\alpha} = 4.46\times10^{-3}\%$, $w_{Nb}^{\alpha} = 2.96\times10^{-3}\% \ll 0.1\%Nb$ (bulk)

- 790℃, The Solubility of NbC in Austenite: $7.26\times10^{-5}\ \%^2$

  PE： $w_c^{\gamma} = 0.144\%$, $w_{Nb}^{\gamma} = 5.04\times10^{-4}\% \ll 0.1\%Nb$ (bulk)

Almost no carbide dissolved during cyclic phase transformation !

Conclusion

- ✓ The cyclic phase transformation experiments have been proposed to study the interaction between the moving α/γ interfaces and IP carbides.
- ✓ According to the dilatometric experiments, 780℃ is defined as the critical unpinning temperature for Fe-0.1C-1.5Mn-0.1Nb steels.
- ✓ The value of pinning force quantitatively determined by the GEB model is approximately 20J/mol, which can generate significant effects on transformation kinetics when the driving force is relatively small. The GEB model including PF can well predict the kinetics of α→γ phase transformation at higher temperature.
- ✓ It can be speculated that almost no carbide is dissolved during cyclic phase transformation based on the thermodynamic analysis.

Thank You