Integrated Models for Predicting the Effect of Manganese Fluctuation on the Phase Transformation of Industrial Hot-Forging Steels

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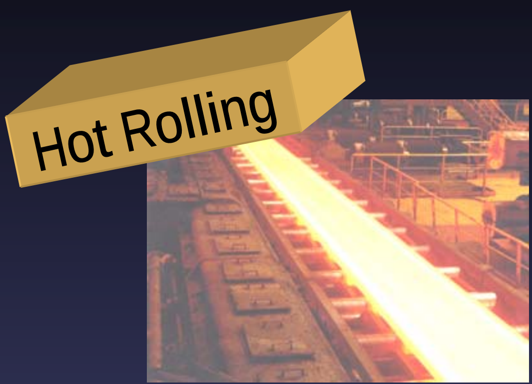
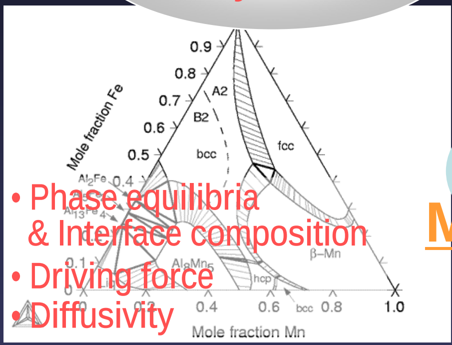
Phase Trans. Modeling in Steel Products



- *'80s-'90s*
  Low-C sheet steel
  ➔ **for α grain size control**
- *Current*
  TRIP / DP steel
  ➔ **for γ_R distribution control**
- '00s-Current
  Medium C-Mn forging steel
  ➔ **Modelling required for the robust microstructure control of forging parts !**

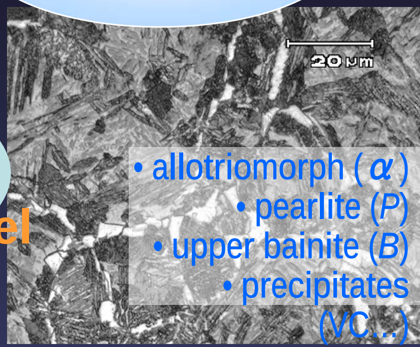
Objective of MCFS Phase Trans. Modeling

CALPHAD thermodynamic calc.



- Phase equilibria & Interface composition
- Driving force
- Diffusivity

Classical nucleation -growth theory



- allotriomorph (*α*)
- pearlite (*P*)
- upper bainite (*B*)
- precipitates (VC...)

Integrated Phase Trans. Model for **Medium-C Forging Steel**

- Predict phase fraction
- Avoid unwanted phase

Effective Controlling of

Good Balance of Properties and Machinability

155th ISIJ Meeting at Musashi Inst. of Tech.

Things to Consider in Phase Trans. of MCFS

- Compositions:
  - 0.2-0.5%C-Si-Mn-(Cr,V), mainly α +*P*
- Growth kinetics of proeutectoid α
  - **Soft impingement** due to C enrichment in γ
  - **Local interface equilibria** - P.E. / N.P.L.E (Mn)
- Accuracy in predicting α→*P* →*B* transitions
  - Variation in C enrichment due to grain size distribution and preceding α

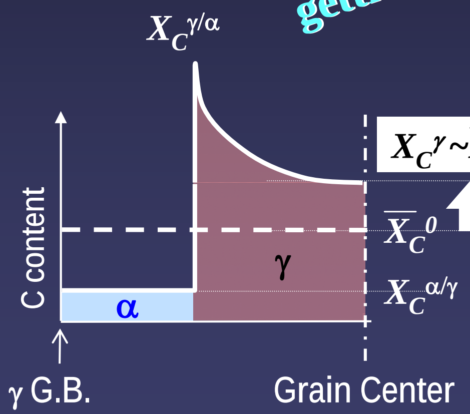
Soft Impingement Effect of Proeutectoid α

- Parabolic growth rate constant; α_1 (*Christian '75*)

$$2\left(\frac{D_C^\gamma}{\pi}\right)^{1/2}\underbrace{\frac{X_C^{\gamma/\alpha}-X_C^\gamma}{X_C^{\gamma/\alpha}-X_C^{\alpha/\gamma}}}=\alpha_1\exp\left(\frac{\alpha_1^{\,2}}{4D_C^\gamma}\right)erf\left(\frac{\alpha_1}{2D_C^{\gamma\,1/2}}\right)$$

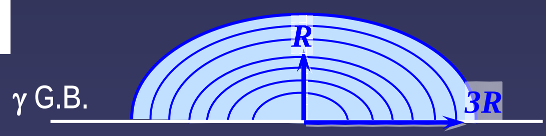
getting slower growth

time dependent α_1



$$X_C^\gamma \sim \overline{X}_C^\gamma = \frac{\overline{X}_C^{\,0}-X_C^{\alpha/\gamma}\cdot V_f(t_{n-1})}{1-V_f(t_{n-1})}$$

- α thickness at t_n



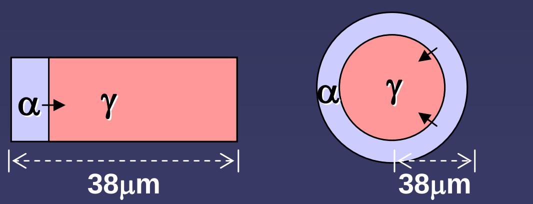
$$R^2(t_n)=\sum_{i=1}^{n}\left(\alpha_1^{\,2}(t_1)\cdot\Delta t_i\right)$$

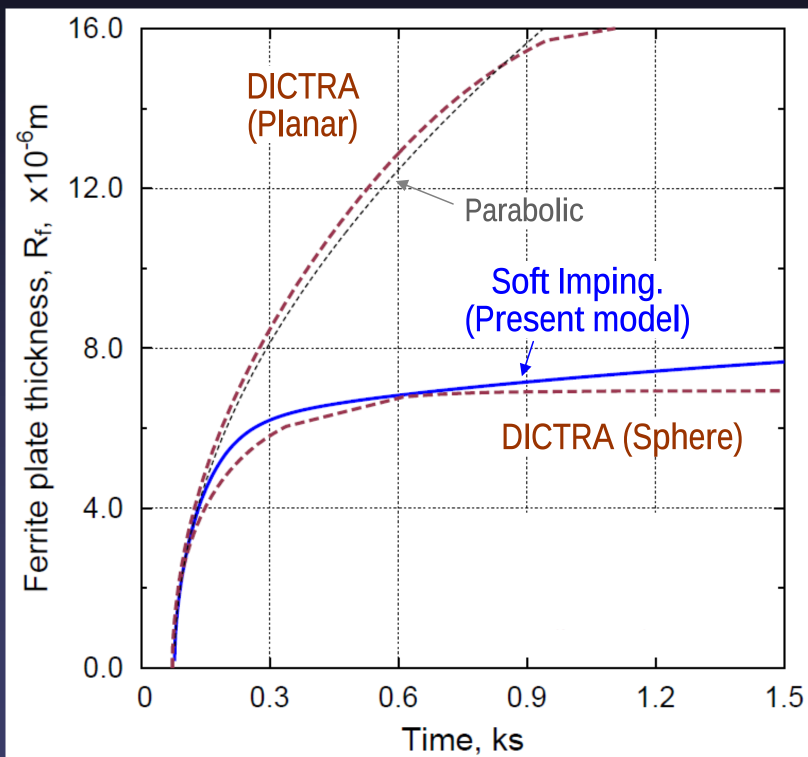
Comparison of α Growth under S.I.E with DICTRA Simulations

- α thickness: R_f

$$R_f=\sqrt{\sum_n\{\alpha_1(n\Delta t)\}^2\Delta t}=\sqrt{\sum_n\left\{f\left(\overline{X}_C^{\gamma,n\Delta t}\right)\right\}^2\Delta t}$$

- DICTRA simulation





Experimental & Calculation Procedure

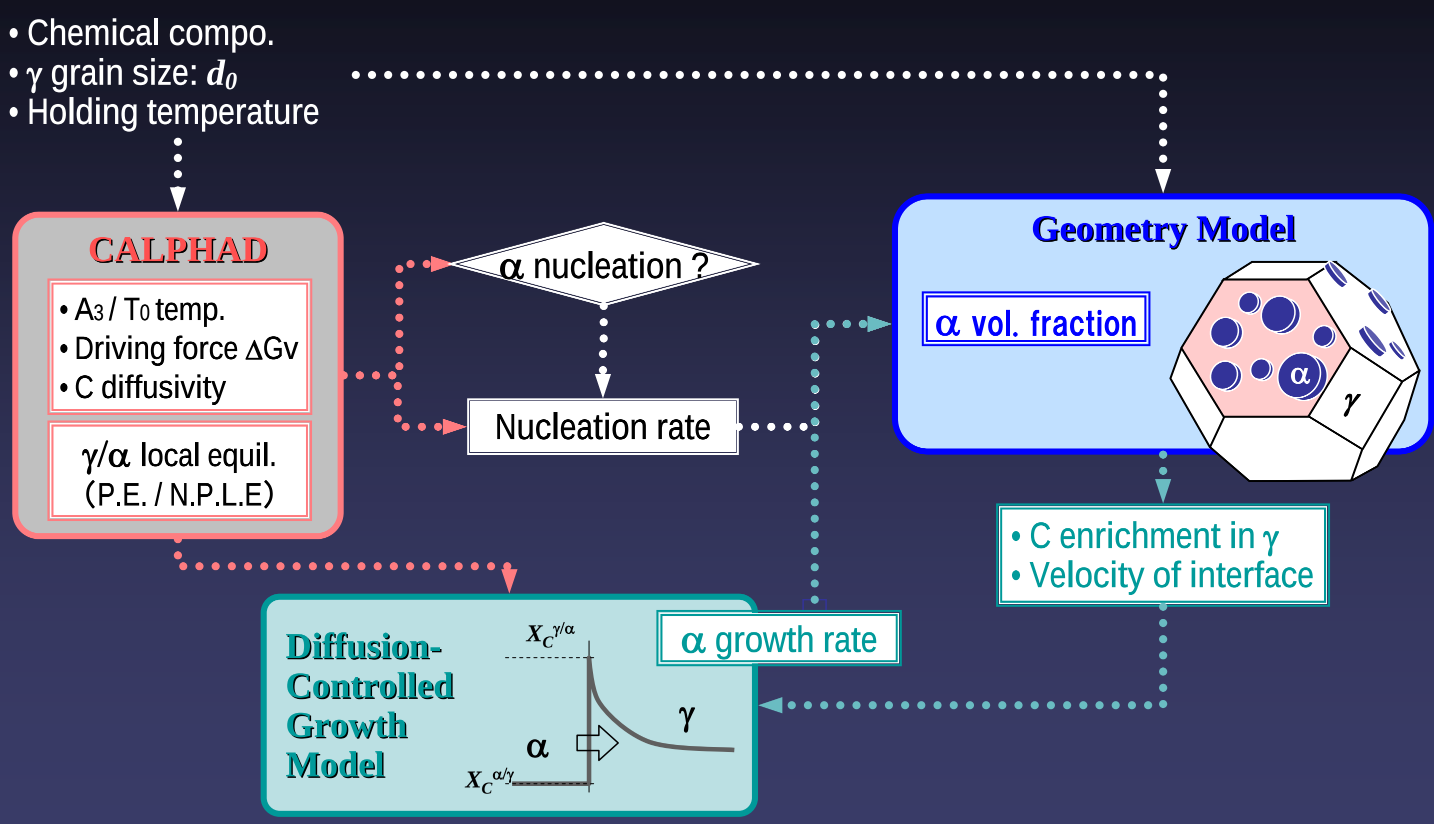
- Steels investigated:

Steel	C	Si	Mn	Ni	Mo	Cr	V	Cu	Al
37V	0.37	0.56	1.45	-	0.03	0.02	0.11	0.14	0.024

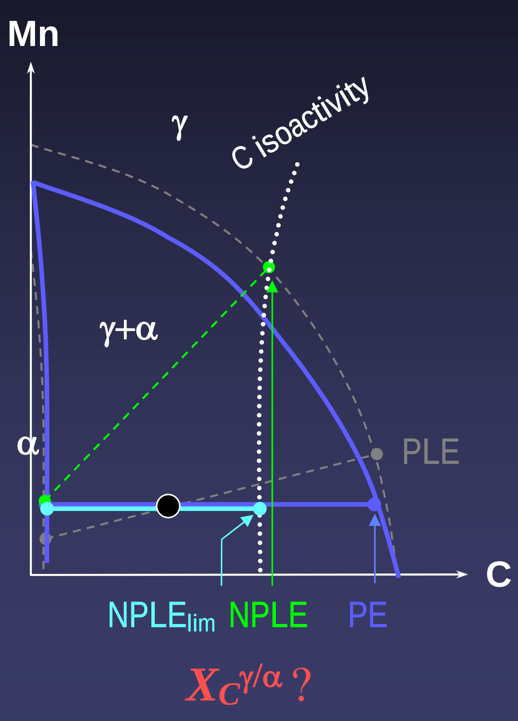
- Measurement of transformation kinetics:
  – Isothermal Test
  - 1523/1273K*60s (d_0=11,76μm) ➡ 973/913/873K*1500s ➡ He jet Q
    (High resolution dilatometry, Quantitative metallography)

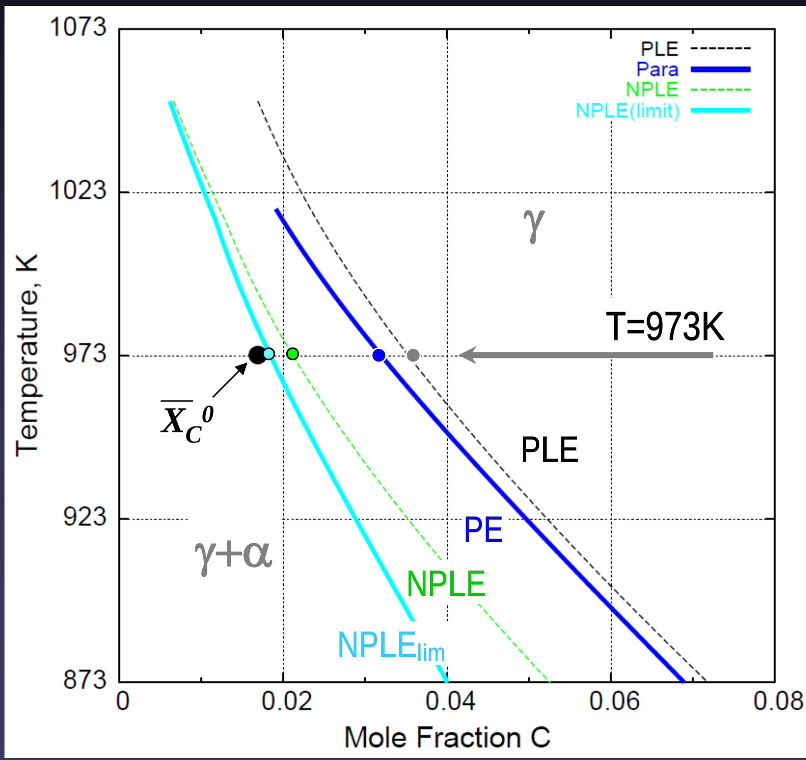
- Calculation:
  – Original program linked with Fortran Inteface "TQ-i"
  – Thermodynamic & Mobility DB: TCFE3 & MOB2

Calc. Flow of the Kinetics of Proeutectoid α



CALPHAD Calculation: γ/α Equilibria (37V)





Comparison with the Detailed Kinetics (37V)

973K, d_0 =76μm

- α incubation time: F_s

  (Lange, Enomoto)

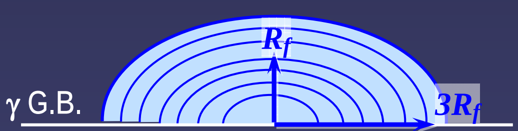
$$\tau = \frac{12kTa^4 \cdot \sigma^{\alpha/\gamma}}{D_C^\gamma \overline{X}_C \cdot v_\alpha^2 \cdot (\Delta G_{\max} / V_m^\alpha)^2}$$

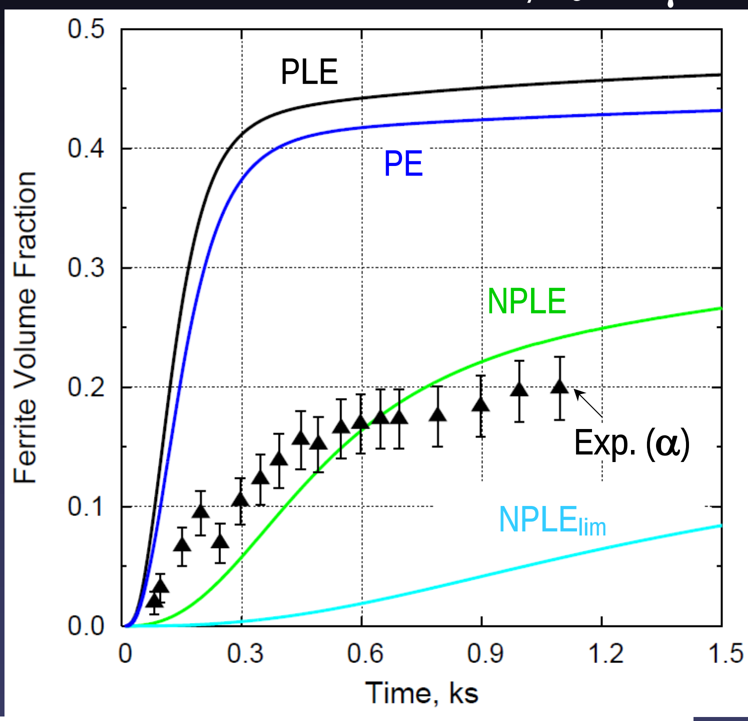
- α nucleation rate: I

  (Aaronson, Umemoto, Yoshie)

$$I = \frac{K_1(1-\overline{X}_C^\gamma)D_C^\gamma}{\sqrt{T}} \exp\left(-\frac{K_2}{RT\Delta G_V^2}\right)$$

- α volume fraction: V_f ***(Umemoto)***





$$V_f(t_n)/V_f^{eq} = 1-\exp\left[-2S_V\int_0^{R(t_n,t_1)} 1-\exp\left(-\sum_{i=1}^{k} I\cdot\Delta t\cdot\pi\left\{R_f^2(t_n,t_i)-y^2\right\}\right)dy\right]$$

D/v criterion for PE to NPLE Transition

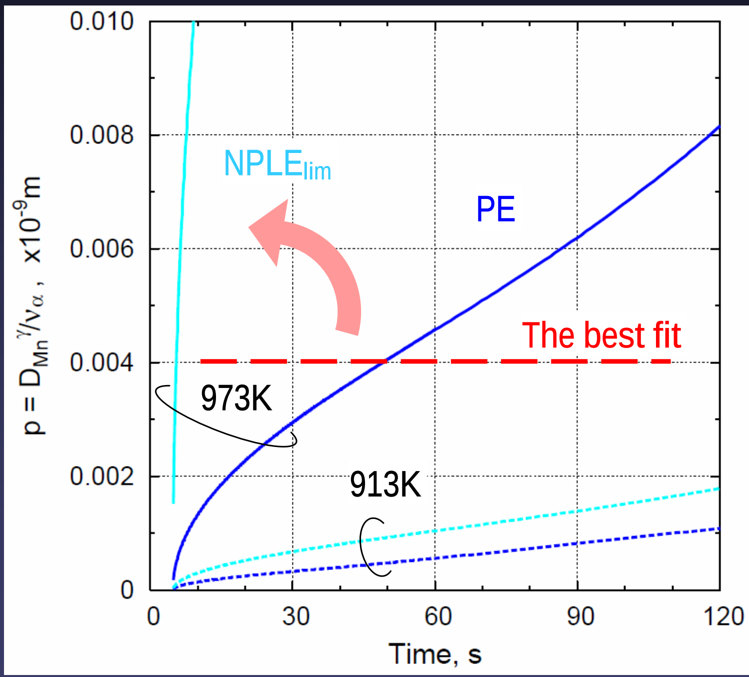
- γ/α Interface velocity: v^α

$$v^\alpha = \frac{dR_f(t)}{dt} = \frac{d\left(\alpha_1\sqrt{t}\right)}{dt} \approx \frac{\alpha_1}{2\sqrt{t}}$$

- D/v criterion: p

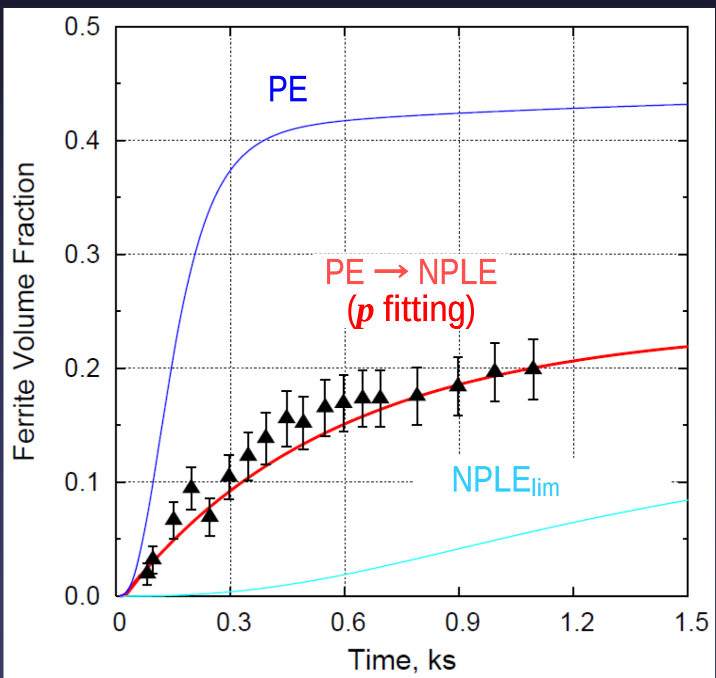
(*Bradley and H.I.Aaronson*)

$$p \equiv \frac{D_{Mn}^{Bound}}{v^\alpha} = \frac{n \cdot D_{Mn}^{\gamma}\sqrt{t}}{\alpha_1}$$

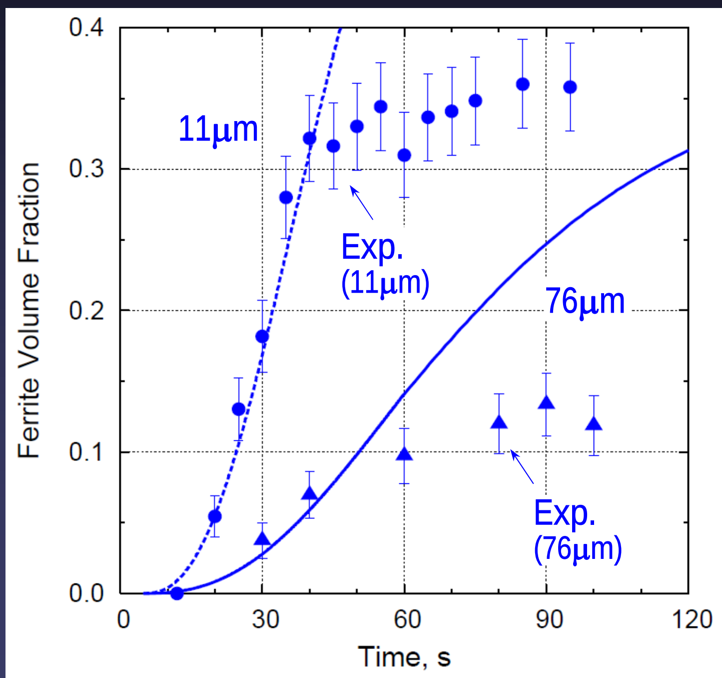


Isothermal Kinetics with D/v criterion (37V)

- 973K, d_0 =76μm



- 913K, d_0 =11, 76μm



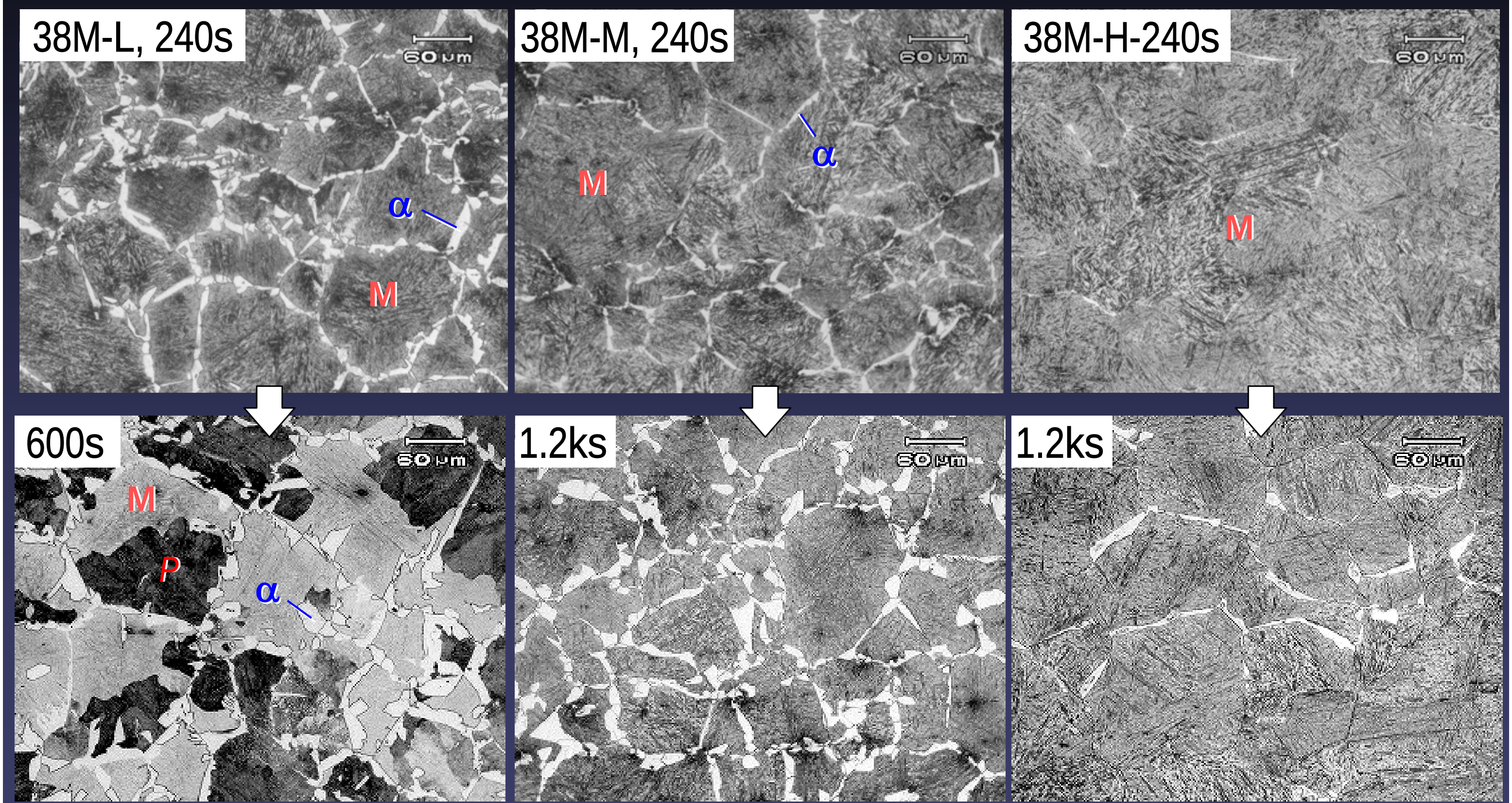
Validation on the Effect of Mn Fluctuation

- Industrial Forging Steels (ASTM1538 grade):

	C	Si	Mn	Ni	Mo	Cr	Cu	Al
38M-H	0.39	0.51	1.69	0.07	0.01	0.15	0.12	0.009
38M-M	0.39	0.50	1.51	0.05	0.01	0.14	0.03	0.009
38M-L	0.39	0.51	1.29	0.06	0.01	0.15	0.11	0.008

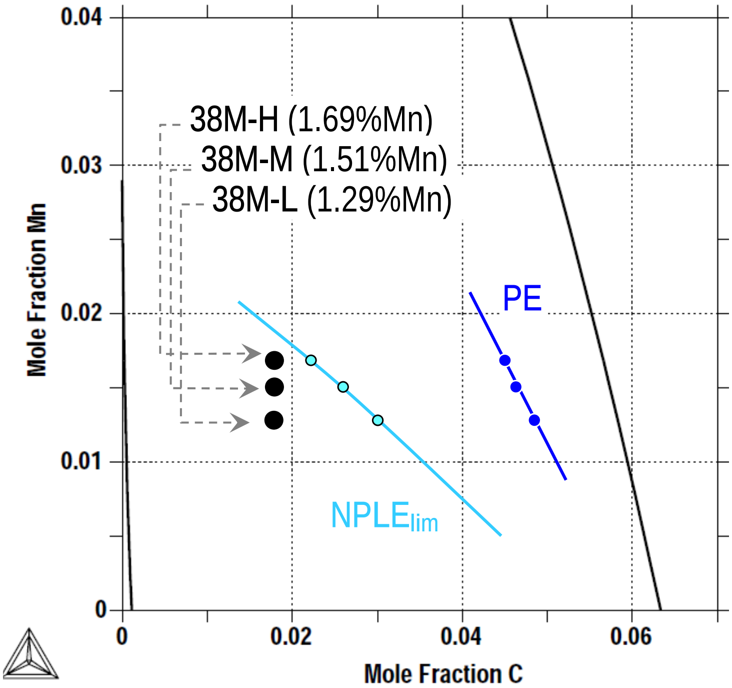
- Measurement of transformation kinetics:
  - Isothermal Test
    - 1173K*70s (d_0=57μm) ➡ 928K*1200s ➡ He jet Q
  - Continues Cooling Test
    - 1173K*70s ➡ from 1063K (Ae3) at 10~100K/min. to 373K (Dilatometry, Quantitative metallography)

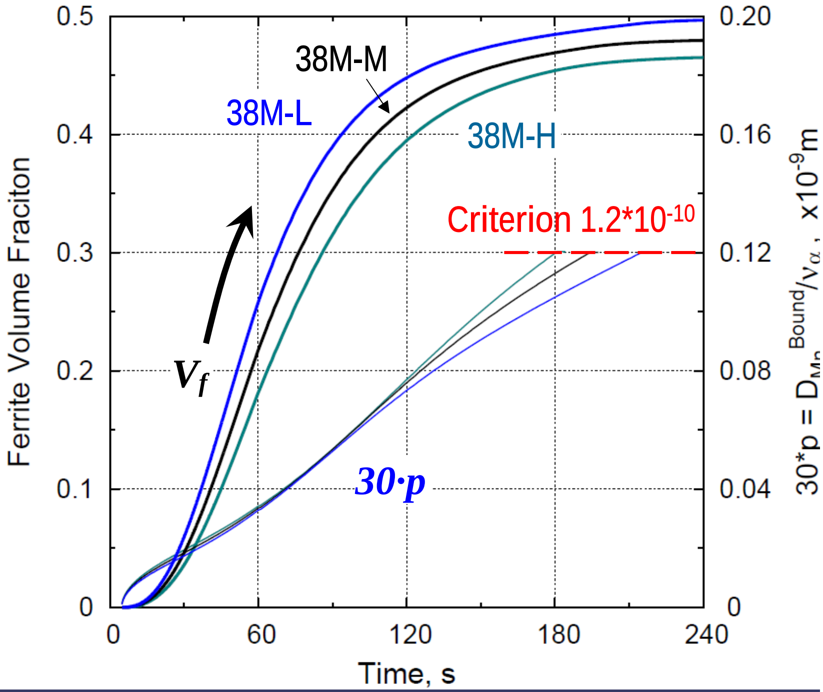
Observed Isothermal Trans. Kinetics (38M)



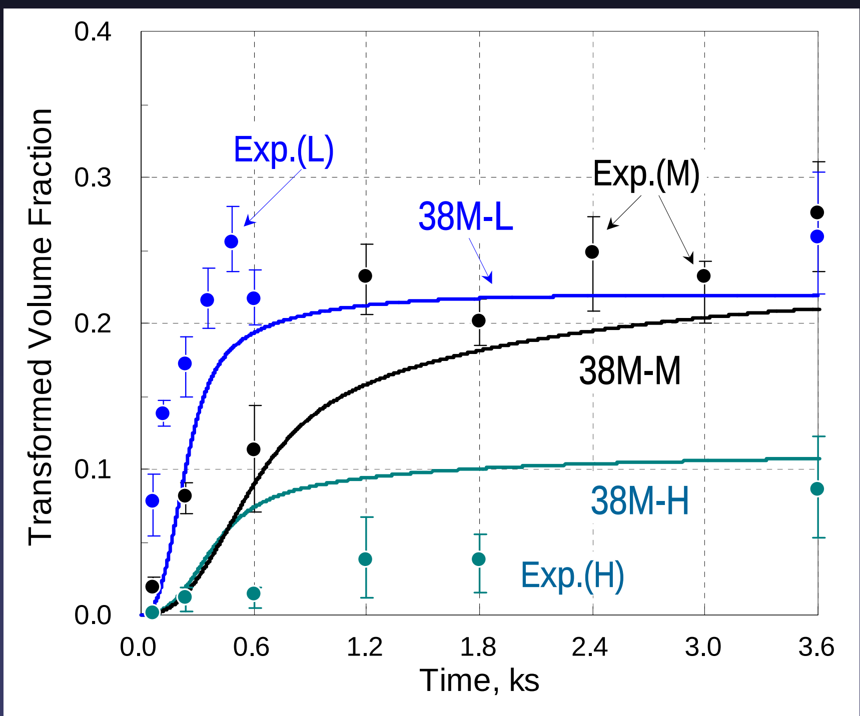
CALPHAD: γ/α Equilibria and D/v Criterion

T=928K





Isothermal Kinetics in γ/α NPLE (38M)

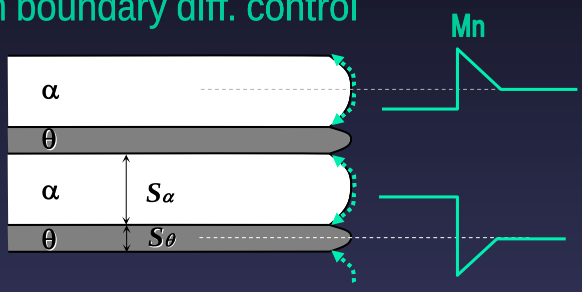


Growth Rate of Pearlite in Fe-C-Mn System

(*Takahashi, Capdevila*)

- LE mode: G_{LE}

Mn boundary diff. control



$$G_{LE} = 12 \underbrace{K^p D_{Mn}^{Bound} \delta}\ \frac{X_{Mn}^{\gamma/\alpha} - X_{Mn}^{\gamma/\theta}}{\overline{X}_{Mn}} \frac{1}{S_\alpha S_\theta}\left(1 - \frac{S_{crit}}{S_0}\right)$$

$$K^p D_{Mn}^B \delta = 2.223 \cdot 10^{-7} \exp\left(-\frac{14940}{RT}\right)$$

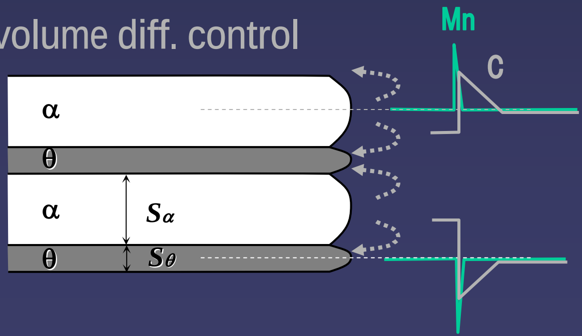
$$S = 1.43 \cdot 10^{-7} - 6.40 \cdot 10^{-10} \cdot (Ae1 - T) \leq 2S_{crit}$$

$$S_{crit} = \frac{2\sigma^{\alpha/\theta}}{6.09 \cdot 10^{-8}}\left(\frac{Ae1}{Ae1 - T}\right)$$

$$\sigma^{\alpha/\theta} = 0.6 J/m^2,\ S_\alpha = 7/8 \cdot S,\ \ S_\theta = 1/8 \cdot S$$

- NPLE mode: G_{NPLE}

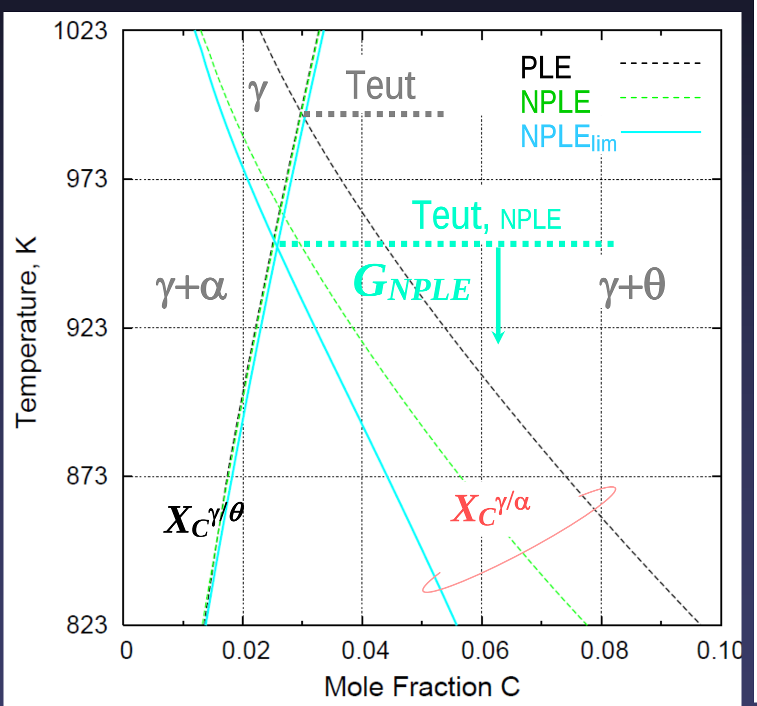
C volume diff. control

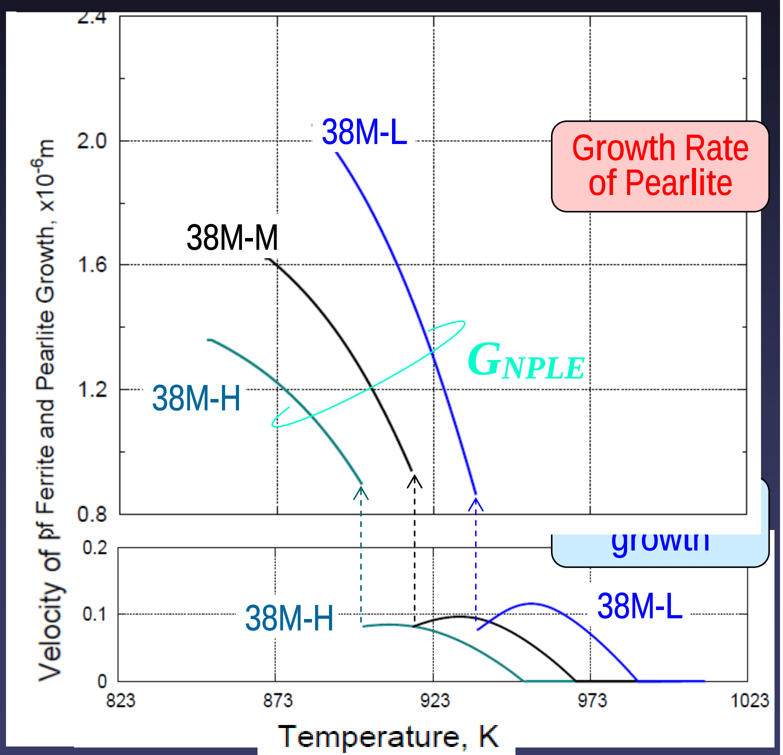


$$G_{NPLE} = \frac{D_C^\gamma}{0.72} \frac{X_{C,NPLE}^{\gamma/\alpha} - X_{C,NPLE}^{\gamma/\theta}}{X_C^{\theta/\gamma} - X_{C,NPLE}^{\alpha/\gamma}} \frac{S}{S_\alpha S_\theta}\left(1 - \frac{S_{crit}}{S_0}\right)$$

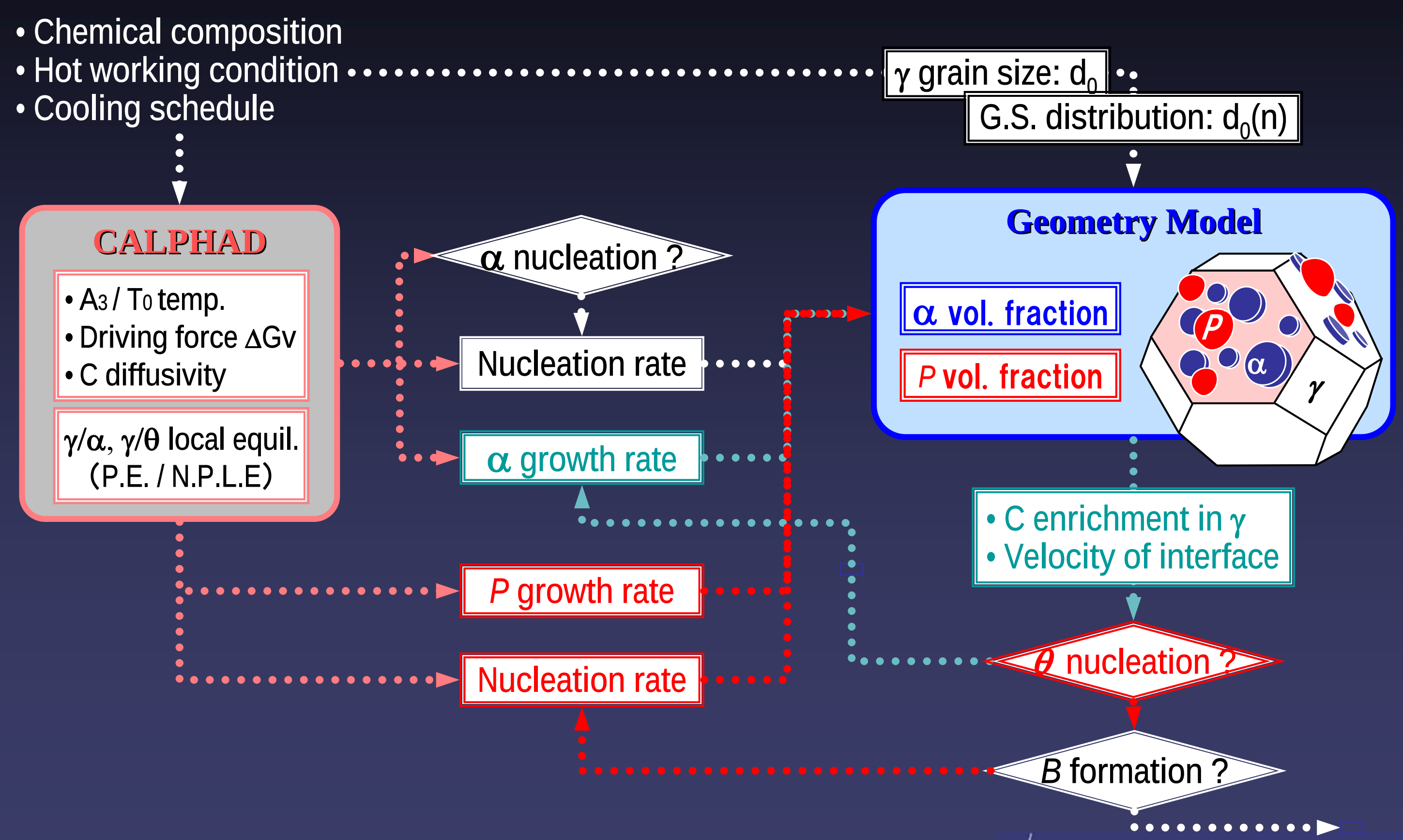
γ/α and γ/θ Equilibria and Pearlite Growth Rate

ex. 38M-M

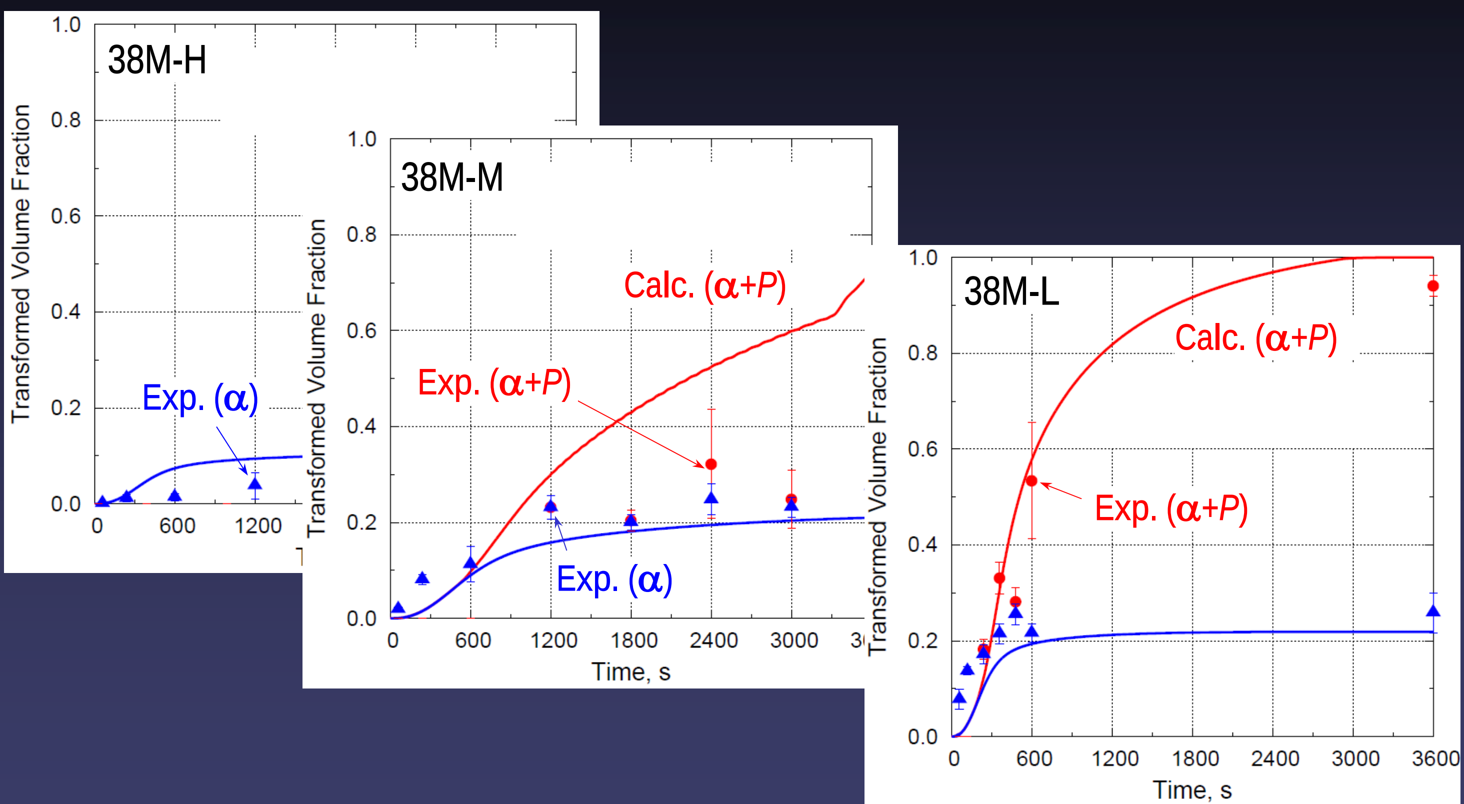




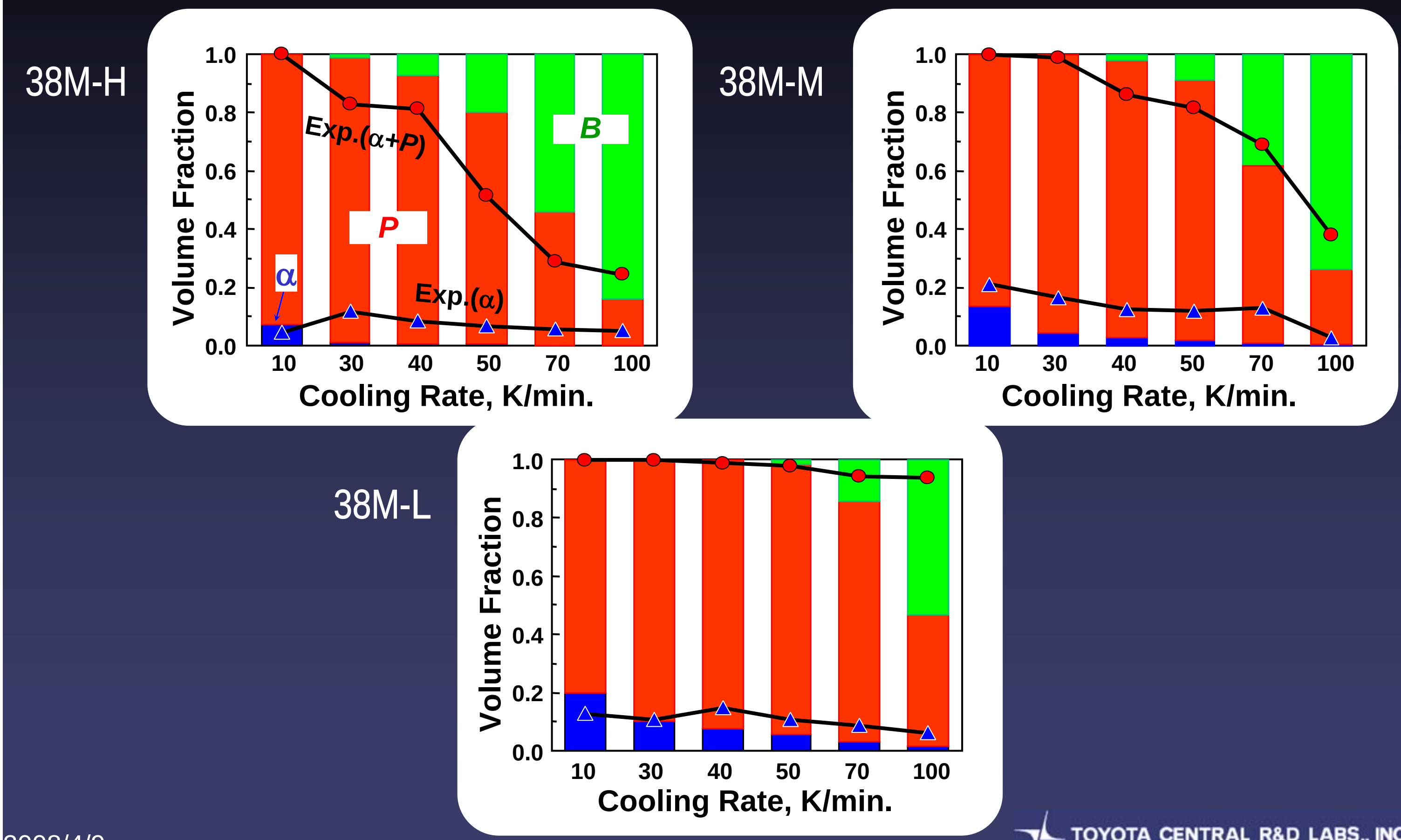
Calc. Flow in The α/P/B Integrated Model



Comparison of Exp. & Calc. α/P Kinetics



Prediction of α/P/B Fractions after Cont. Cool.



Summary

Features in the integrated phase transformation model for MCFS include:

1. Time-dependent α_1 of proeutectoid α (S. I. E.)
2. γ/α interface equilibrium transition to NPLE
3. Integration of *P* kinetics and *B* prediction from thermodynamics of remaining γ

The calculation reproduced well the slow *α* growth kinetics, but the problem of inconsistent *D/v* criteria remains.

The program showed an ability of predicting the difference in isothermal / continues cooling transformation kinetics caused by a minor Mn fluctuation.