ALEMI-V
（Grenoble,2006.5.8
）

The Incomplete Transformation of Upper Bainite in Low-carbon HSLA Steels by Nb addition

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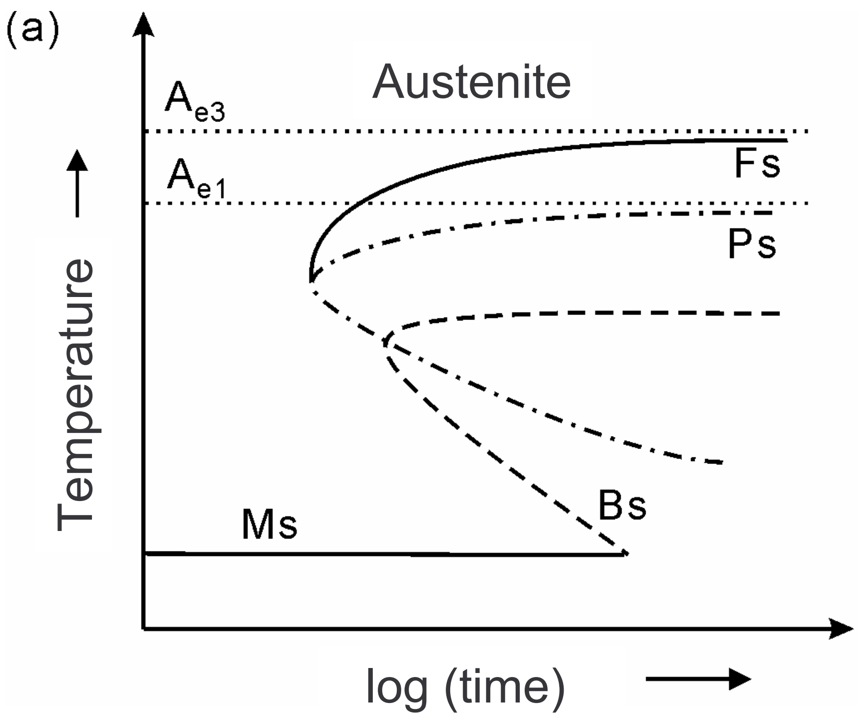
Funded by CBMM Asia.

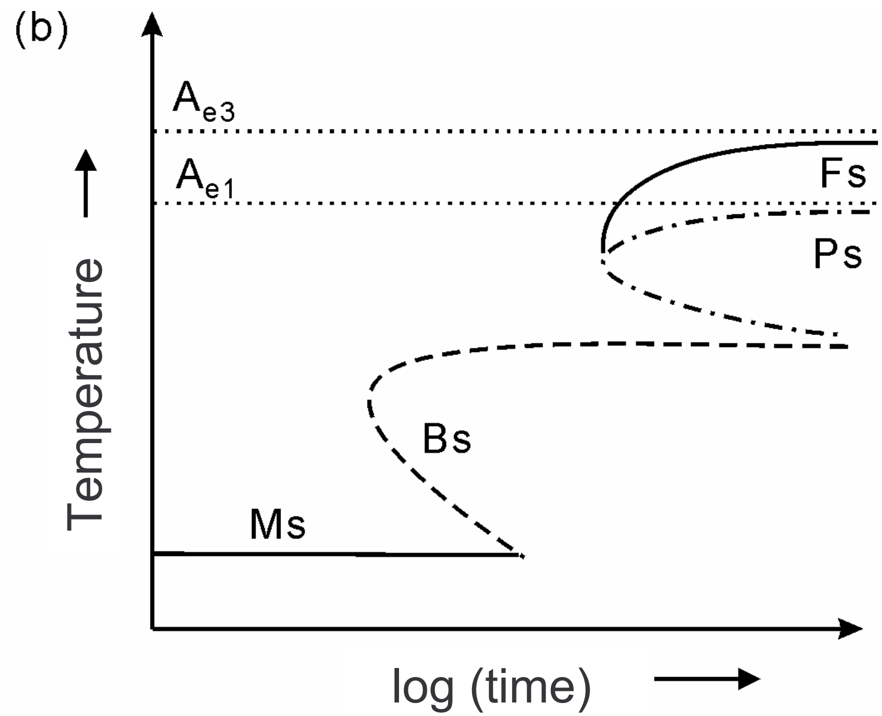
Effect of Alloying Element on TTT diagram

Carbon, Ni, Mn

Mo, Cr, V
(strong carbide former)

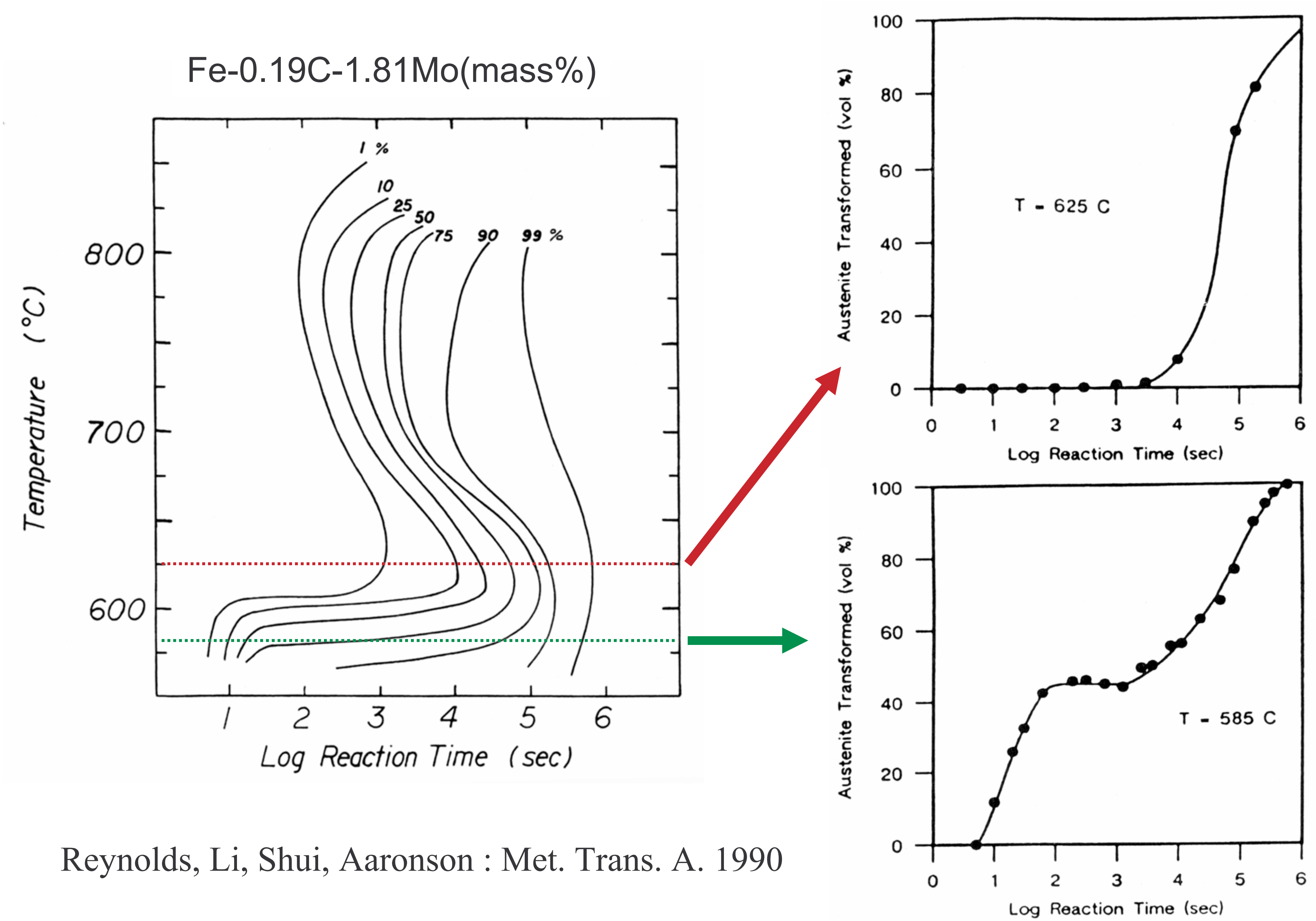


Single C-curve



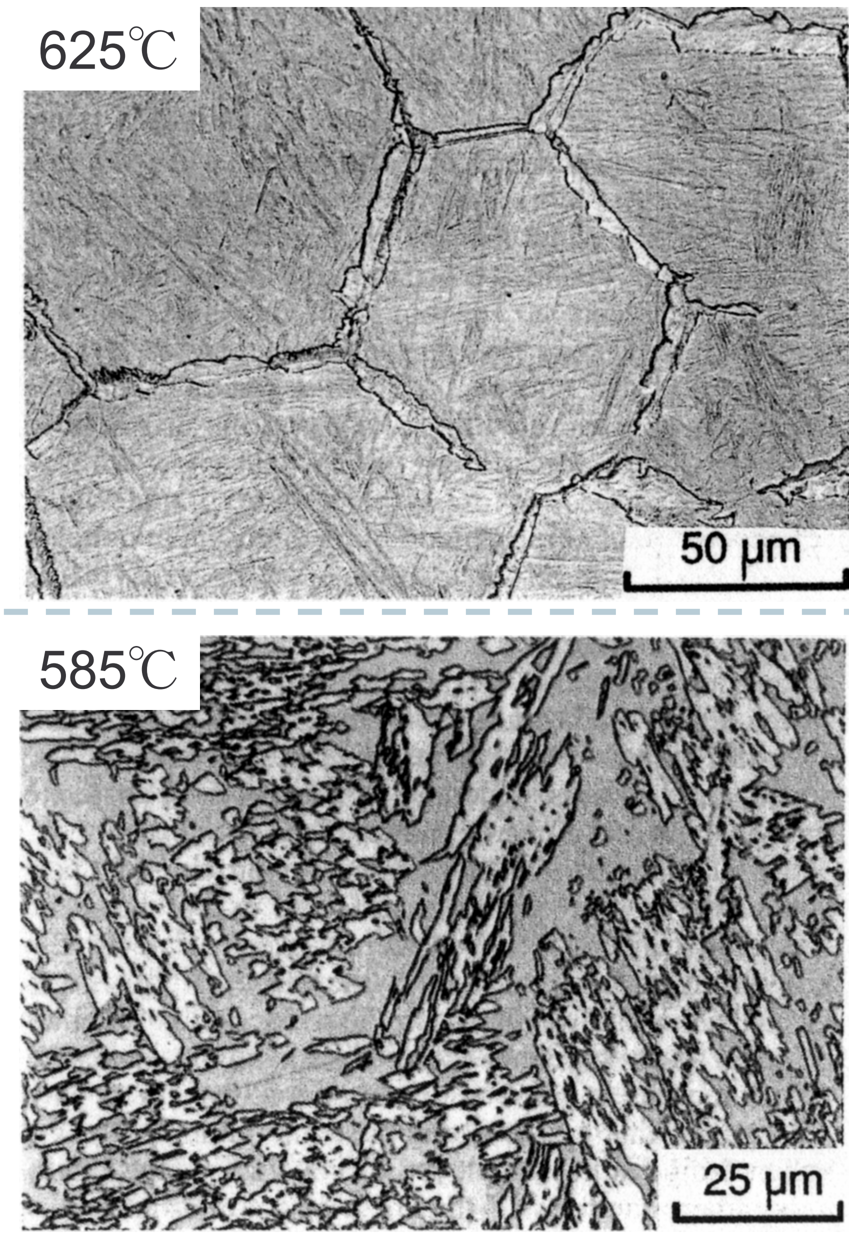
Double C-curve
(kinetic-Bs)

Transformation stasis (Incomplete transformation)

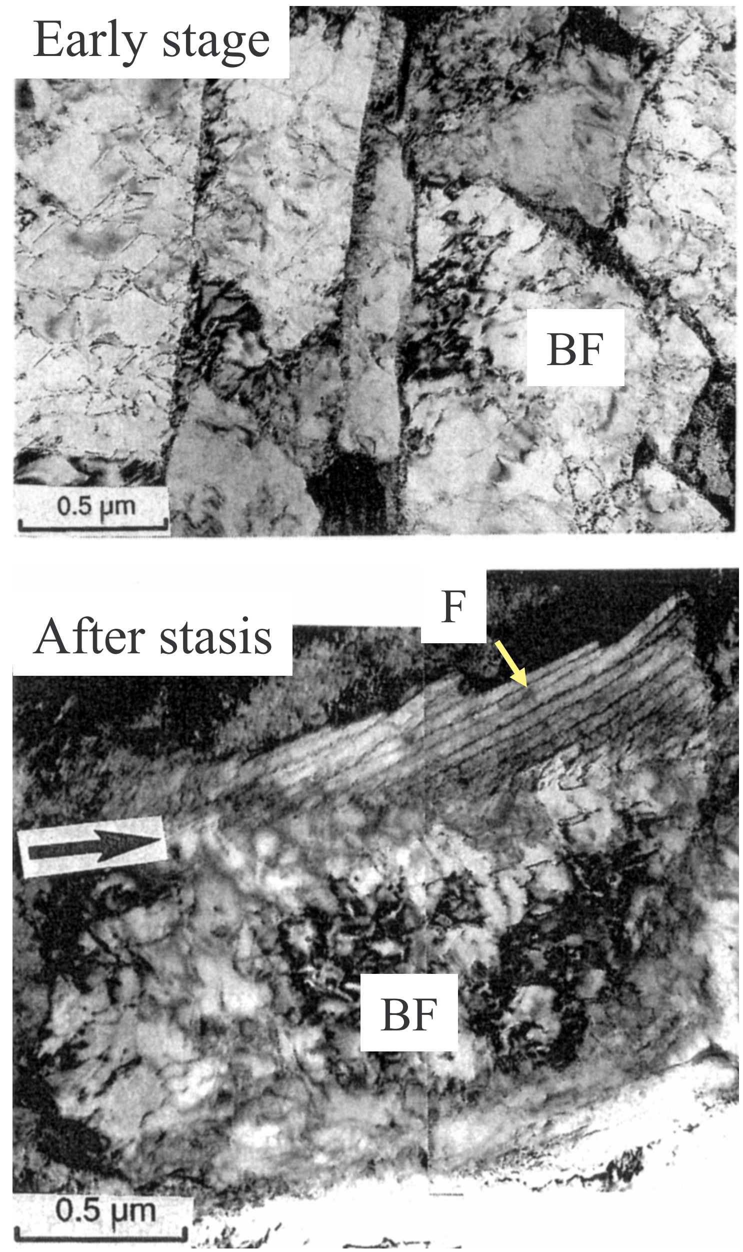


Reynolds, Li, Shui, Aaronson : Met. Trans. A. 1990

Optical micrograph



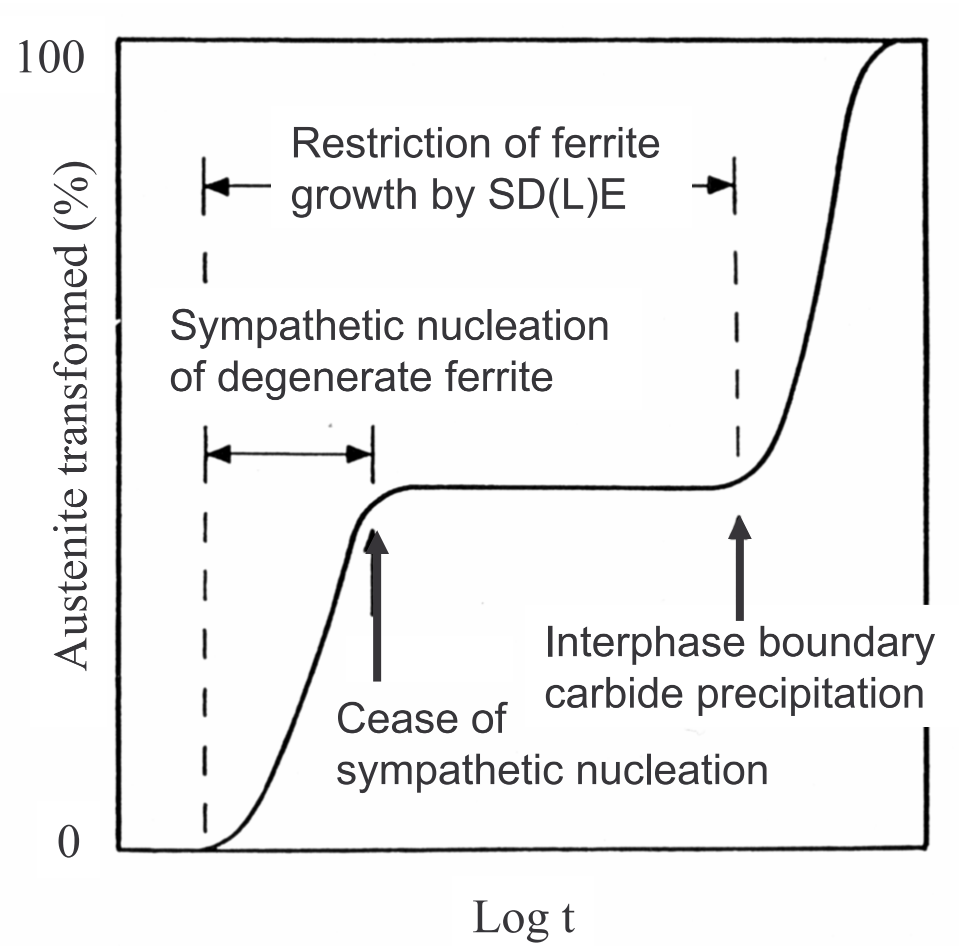
Transmission electron micrograph



Reynolds, Li, Shui, Aaronson : Met. Trans. A. 1990

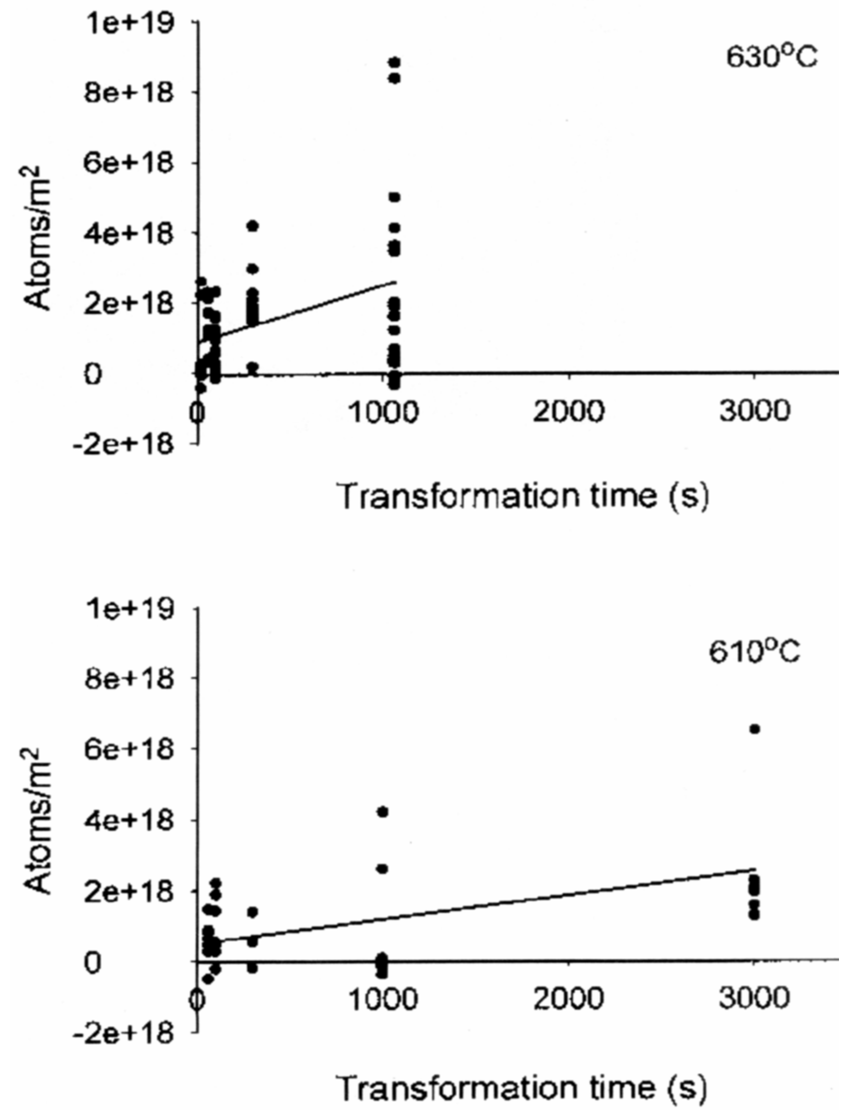
Explanation of the transformation stasis below the bay by SD(L)E

(Reynolds et al : Met. Trans. A. 1990)

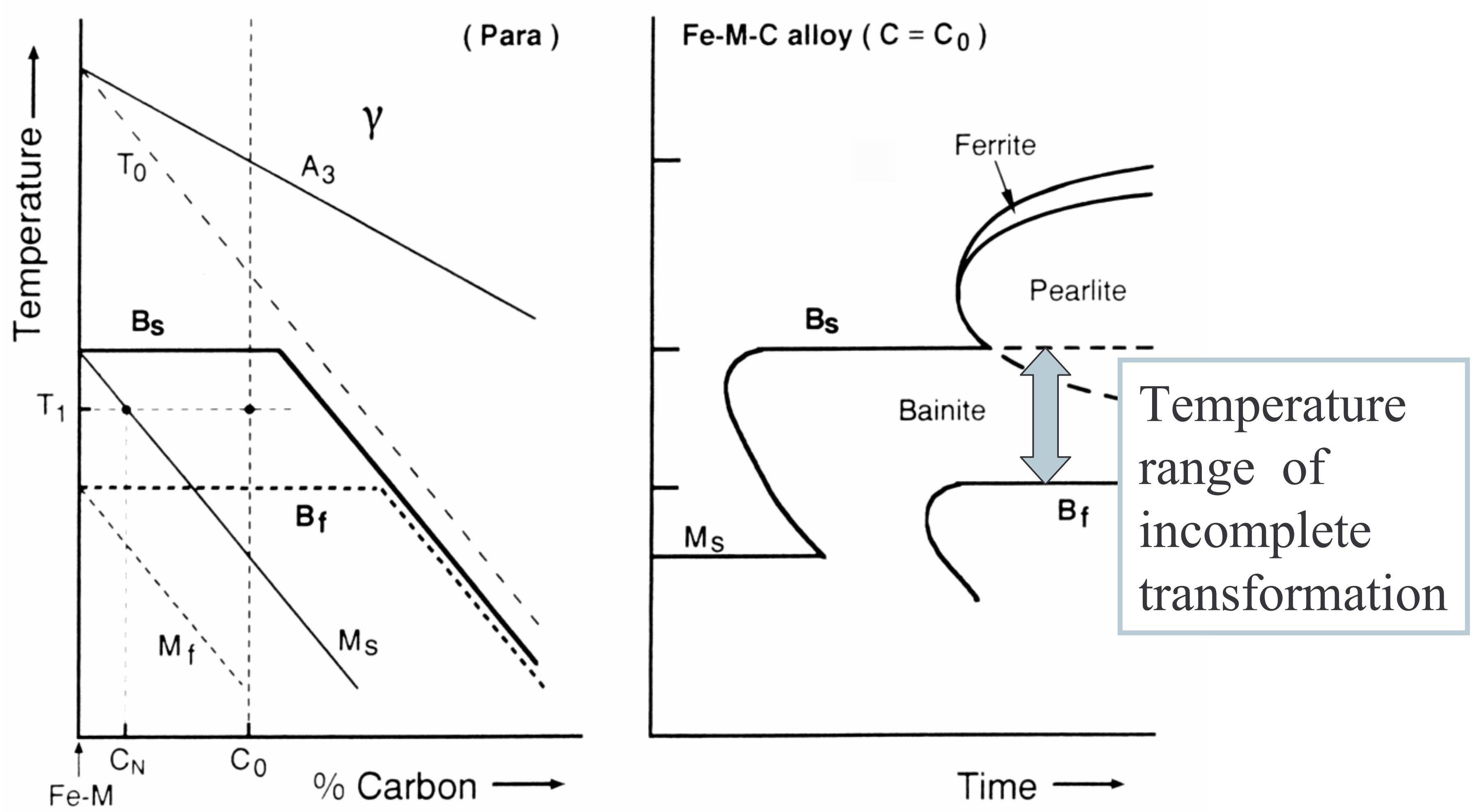


Increase in Mo segregation

(Humphery et al: MMTA, 2004.)



Kinetics Bs of Fe-C-Mn ≒ Ms temperature of Fe-M



(K. Tsuzaki, K. Fujiwara, T. Maki: Mater. Trans., JIM, 32(1991), 667-678)

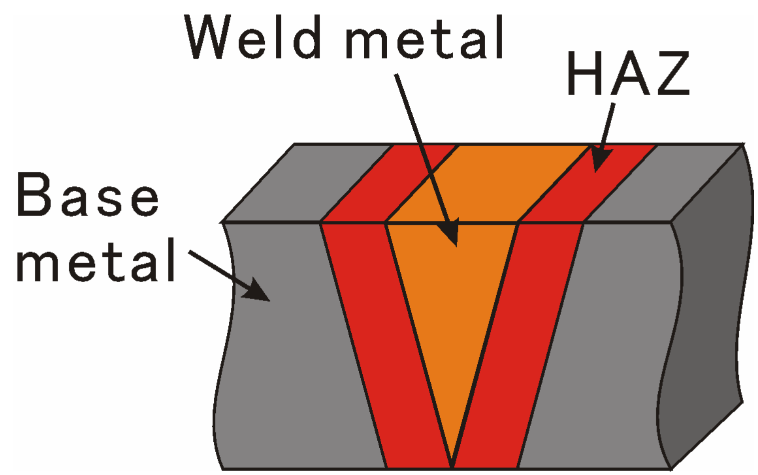
Heat affected zone (HAZ)

Transformation during fast cooling from coarse γ grains

Formation of island of martensite or M/A constituent

⇓

Degradation of toughness

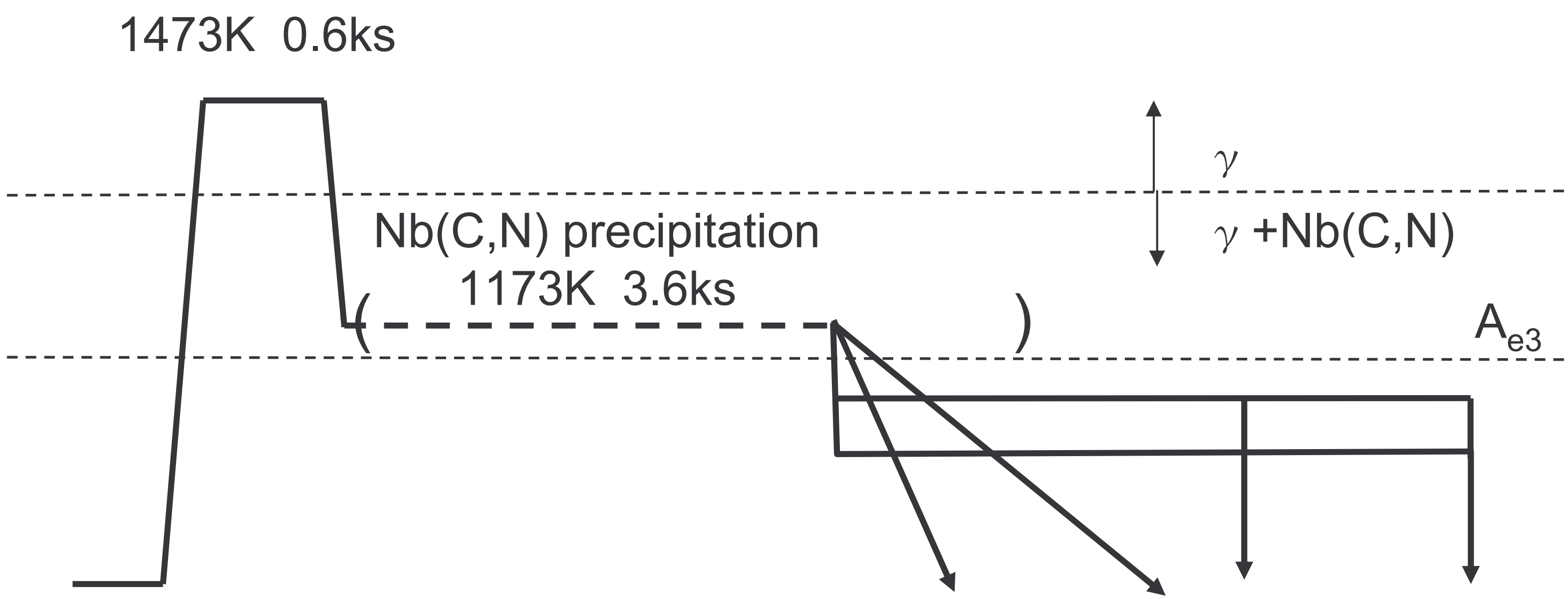


In high-strength, low-alloy (HSLA) steel microalloyed with Nb, the amount of M(/A) increases remarkably.

Experimental

Materials Fe-(0.05 or 0.15)C-1.5Mn-(0 - 0.030)Nb (mass%)

Heat treatment

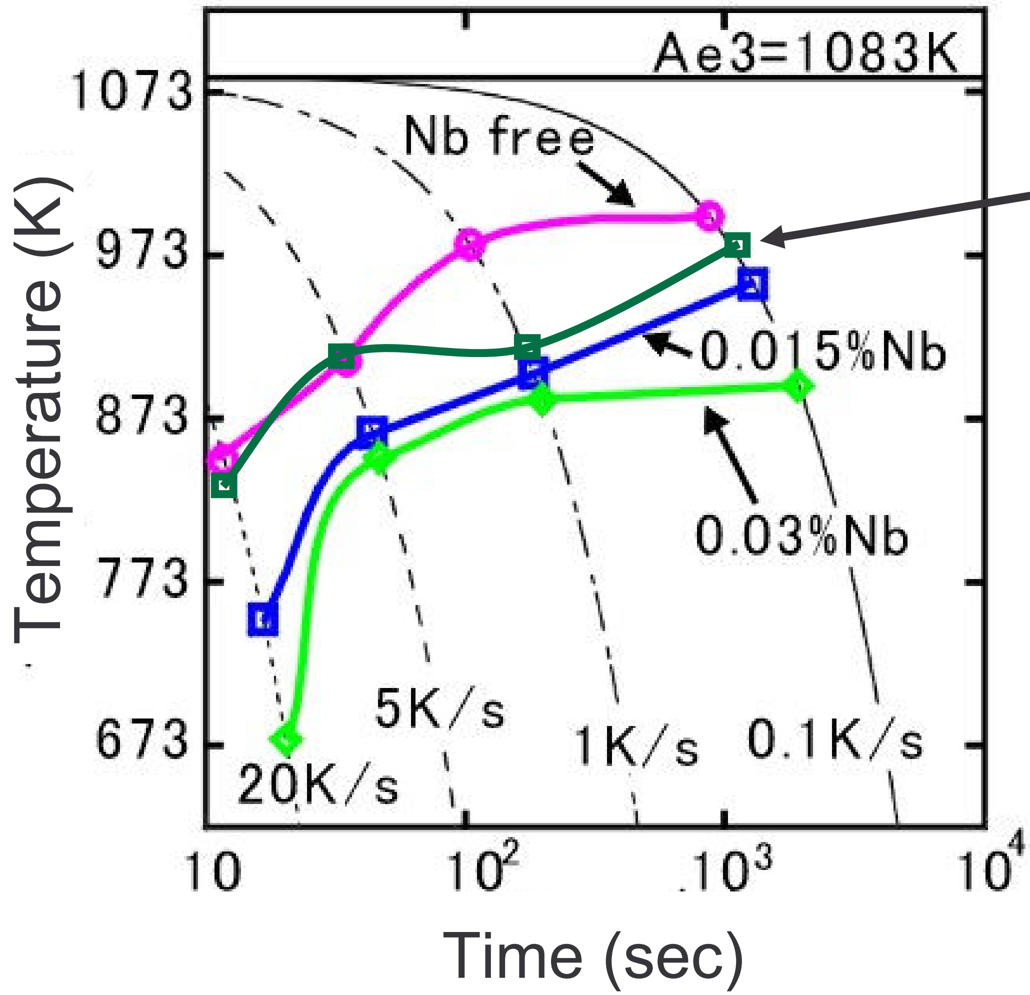


Continuous cooling: cooled at 0.1 ~ 20 K/s

Isothermal holding : 723 ~ 973 K ~86.4ks

Effect of Nb addition on transformation temperature in CCT

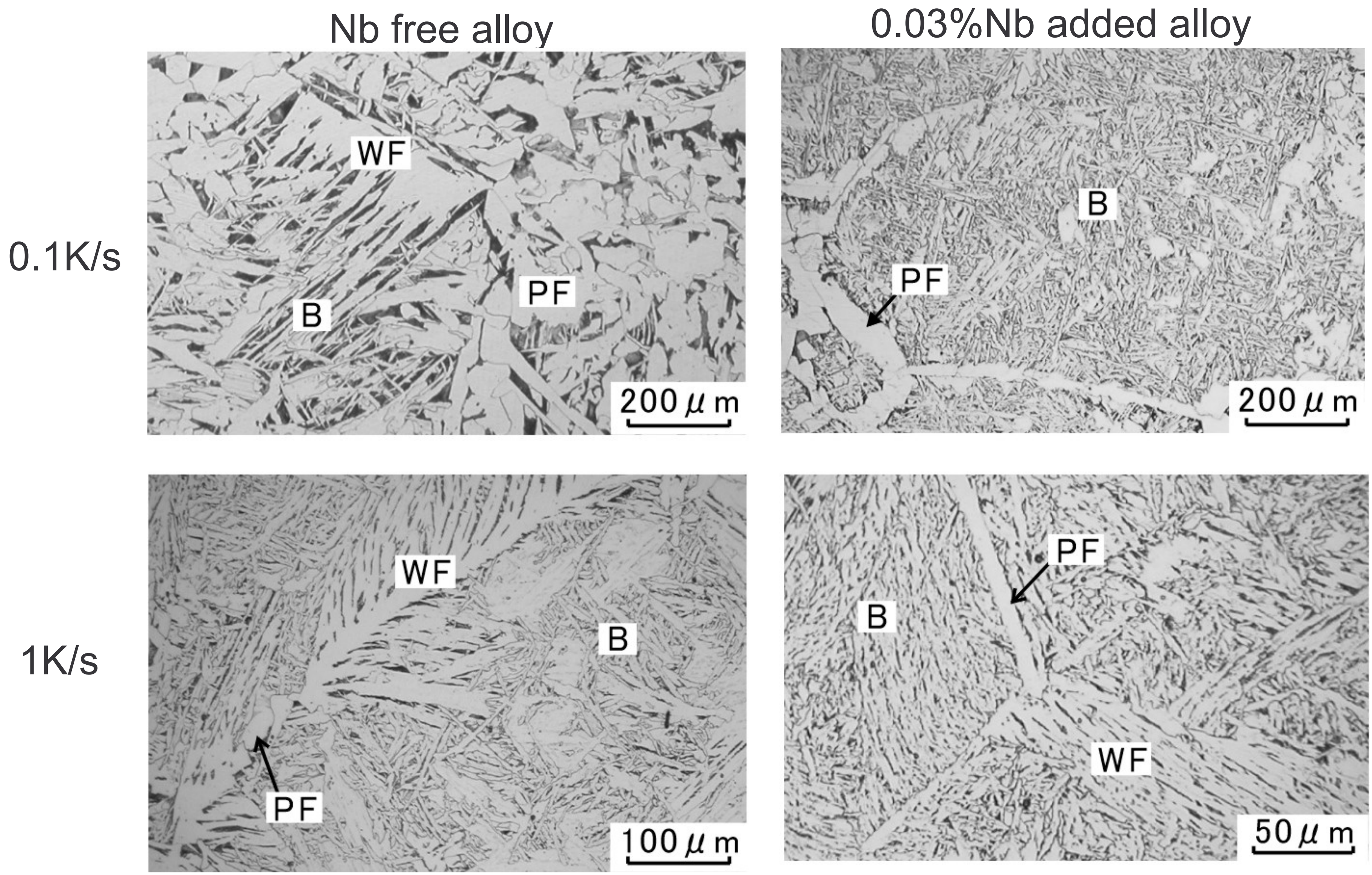
Fe-0.15C-1.5Mn



- Transformation temperature ↓ as Nb content in solution ↑ .
- Precipitation of Nb(C,N) results in a smaller decrease in transformation temperature.

Continuous cooling transformation (OM) Fe-0.15C-1.5Mn

PF : Polygonal Ferrite WF :Widmanstätten Ferrite B : Bainite

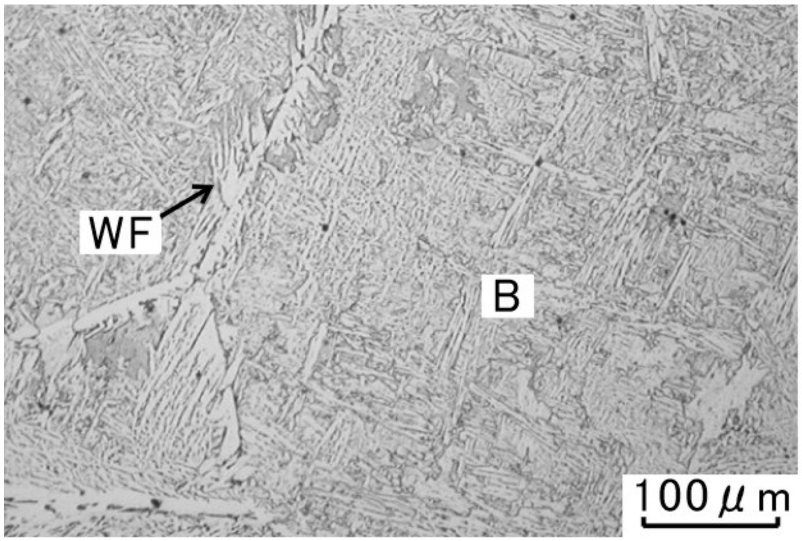


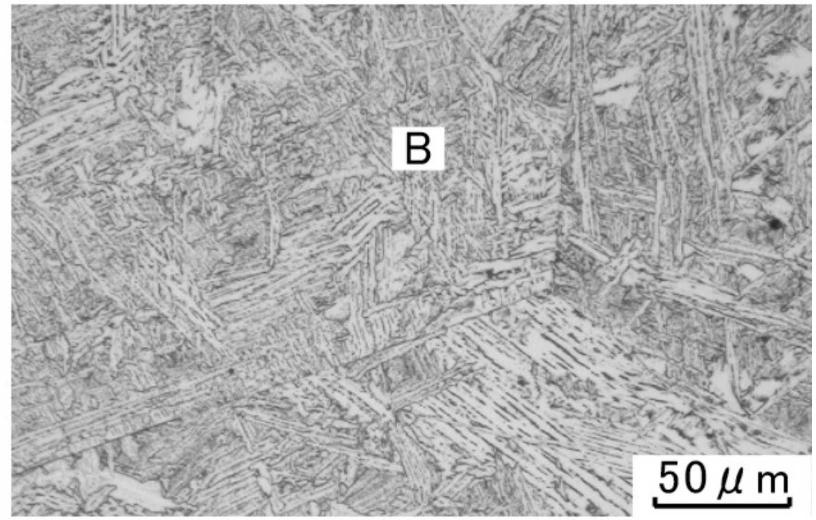
Continuous cooling transformation (OM) Fe-0.15C-1.5Mn

WF :Widmanstätten Ferrite B : Bainite M : Martensite

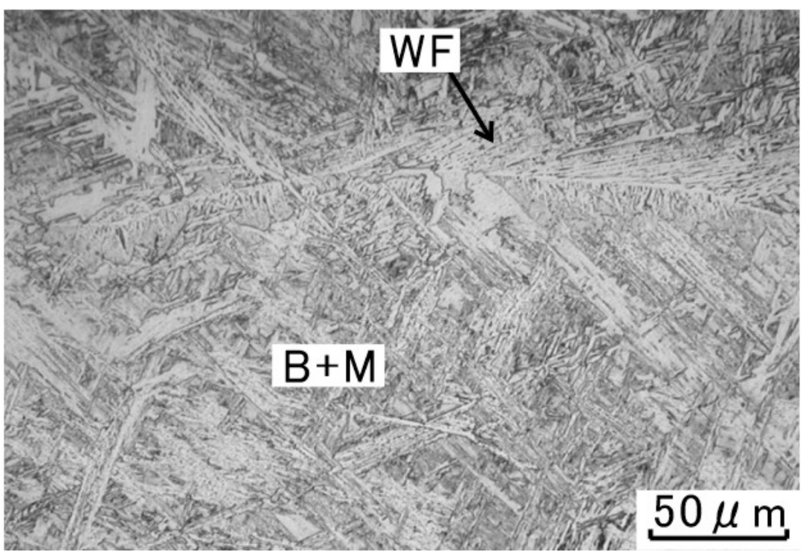
Nb free alloy | 0.03%Nb added alloy

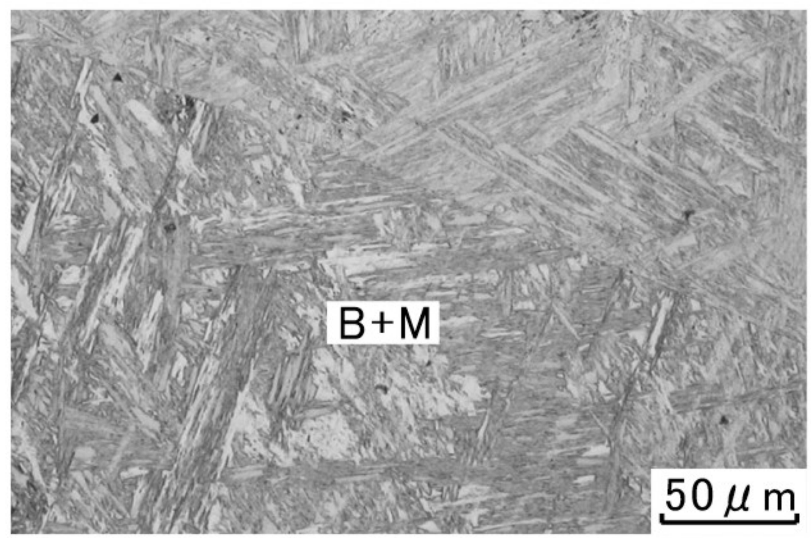
5K/s





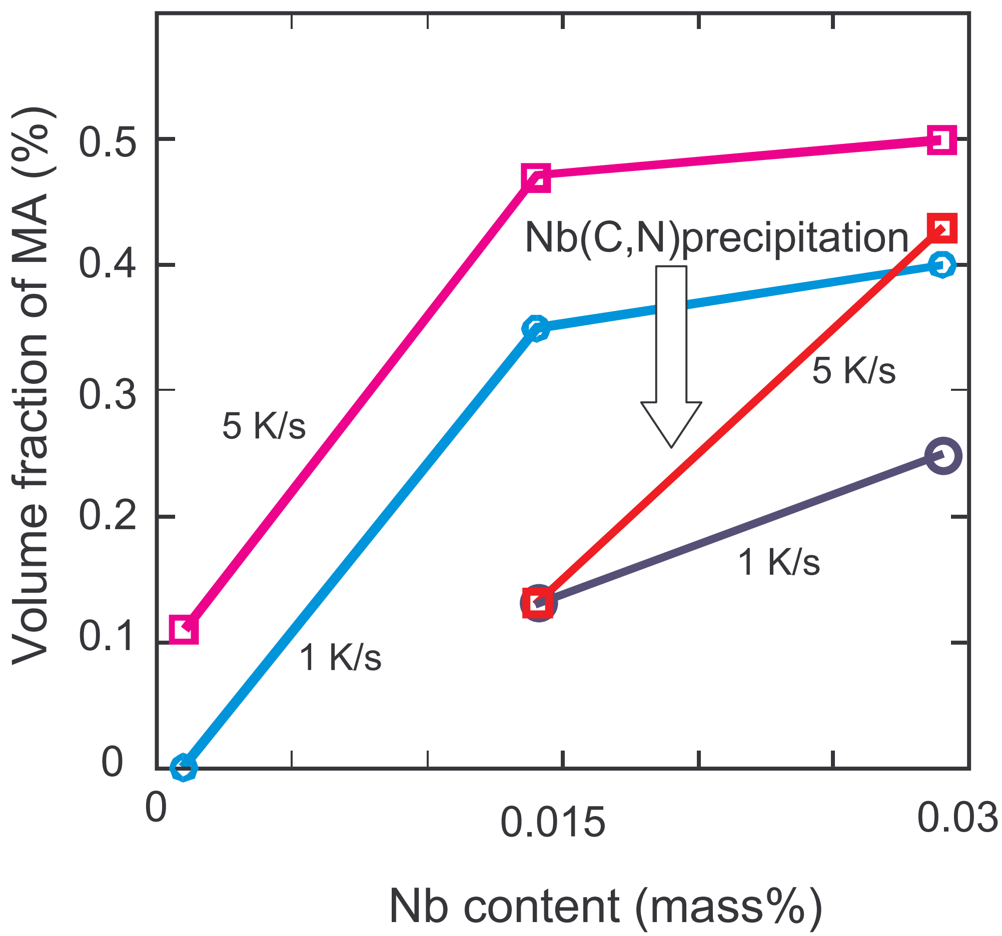
20K/s



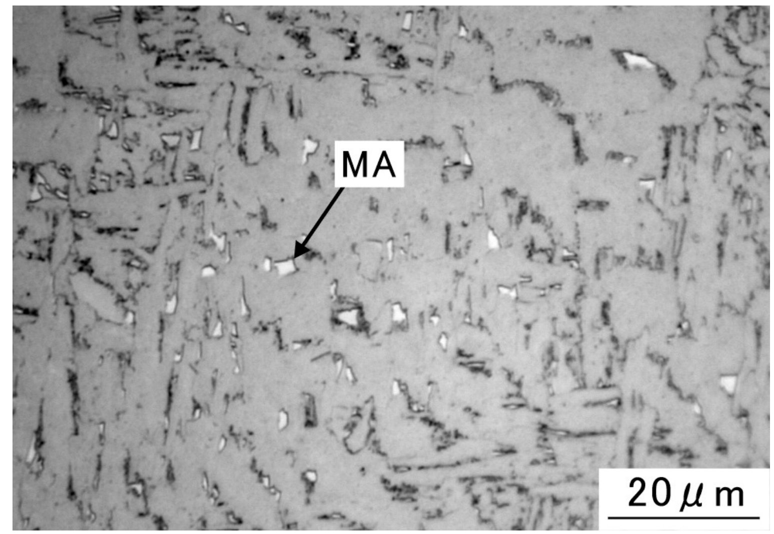


MA formed during continuous cooling

Fe-0.15C-1.5Mn



0.015%Nb added alloy, cooled at 5K/s

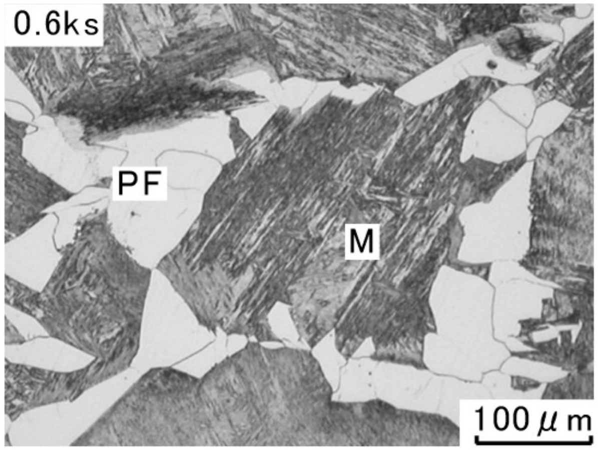


- The amount of MA ↑ as Nb content in solution ↑ .
- Precipitation of Nb(C,N) results in a smaller fraction of MA.

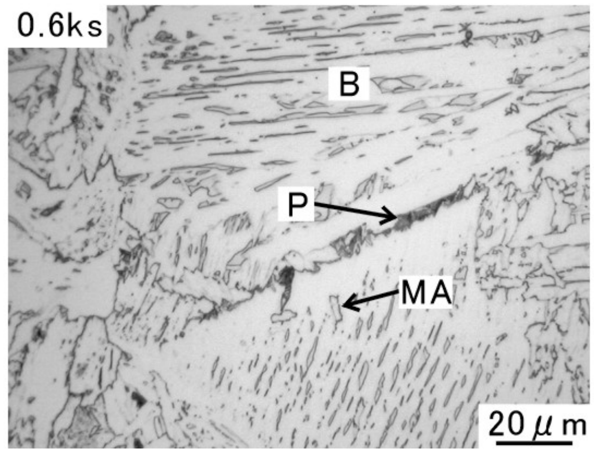
Isothermal transformation (OM)

PF : Polygonal Ferrite P :Pearlite M : Martensite
B : Bainite MA :Martensite-Austenite constituent

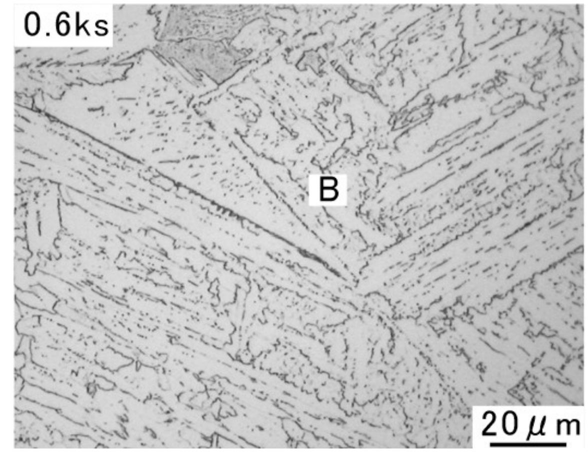
Fe-0.15C-1.5Mn (Nb free alloy)



973K

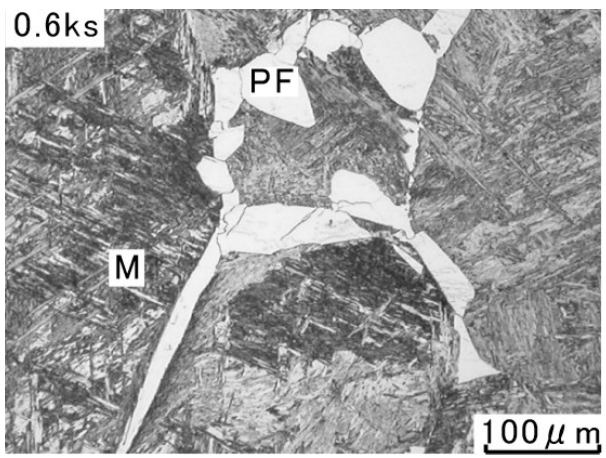


823K

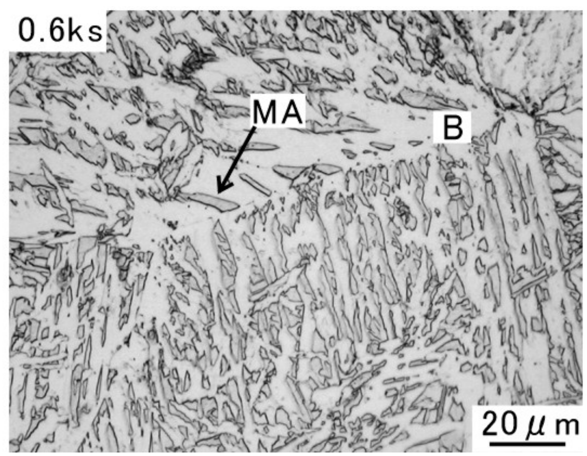


773K

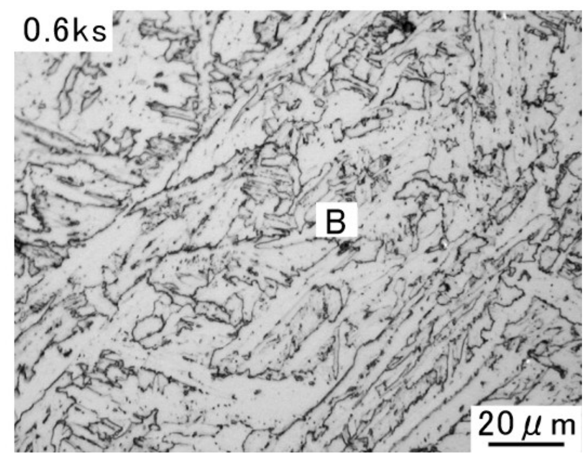
0.03%Nb added alloy



973K



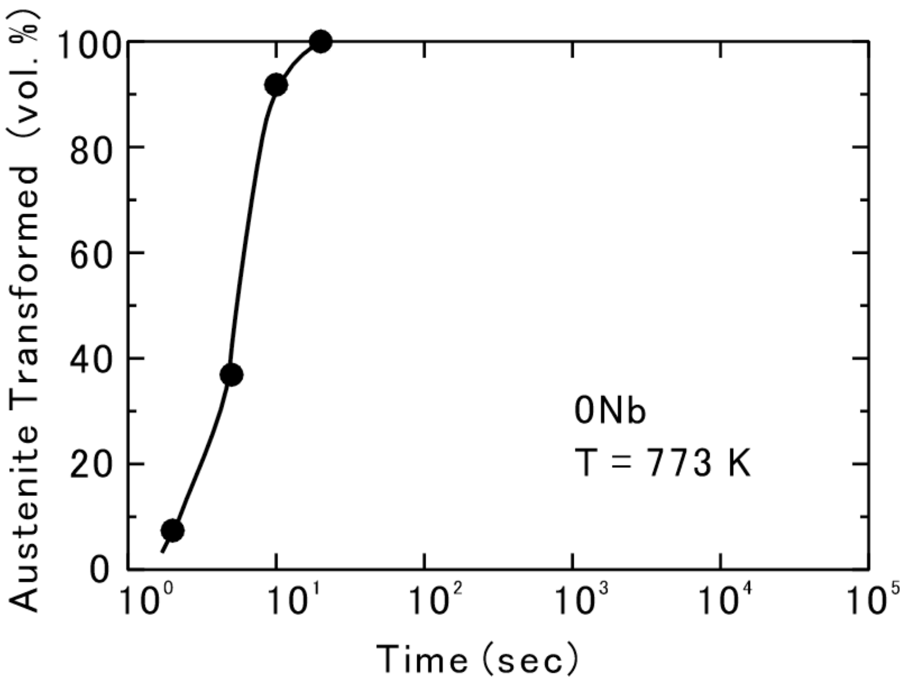
823K



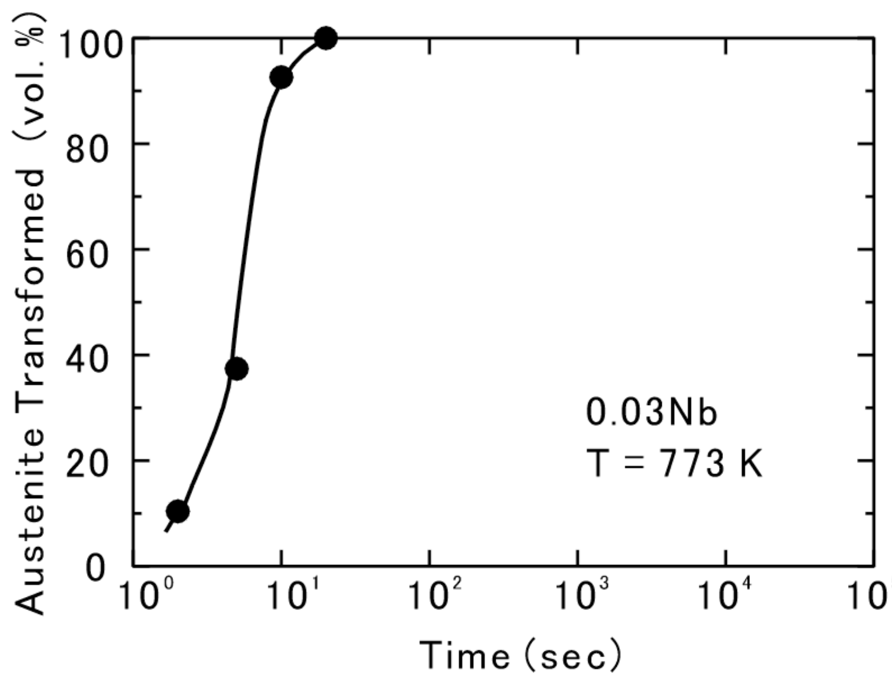
773K

Fe-0.15C-1.5Mn-(0, 0.03Nb) , transformed at 773K

Nb free alloy



0.03%Nb added alloy

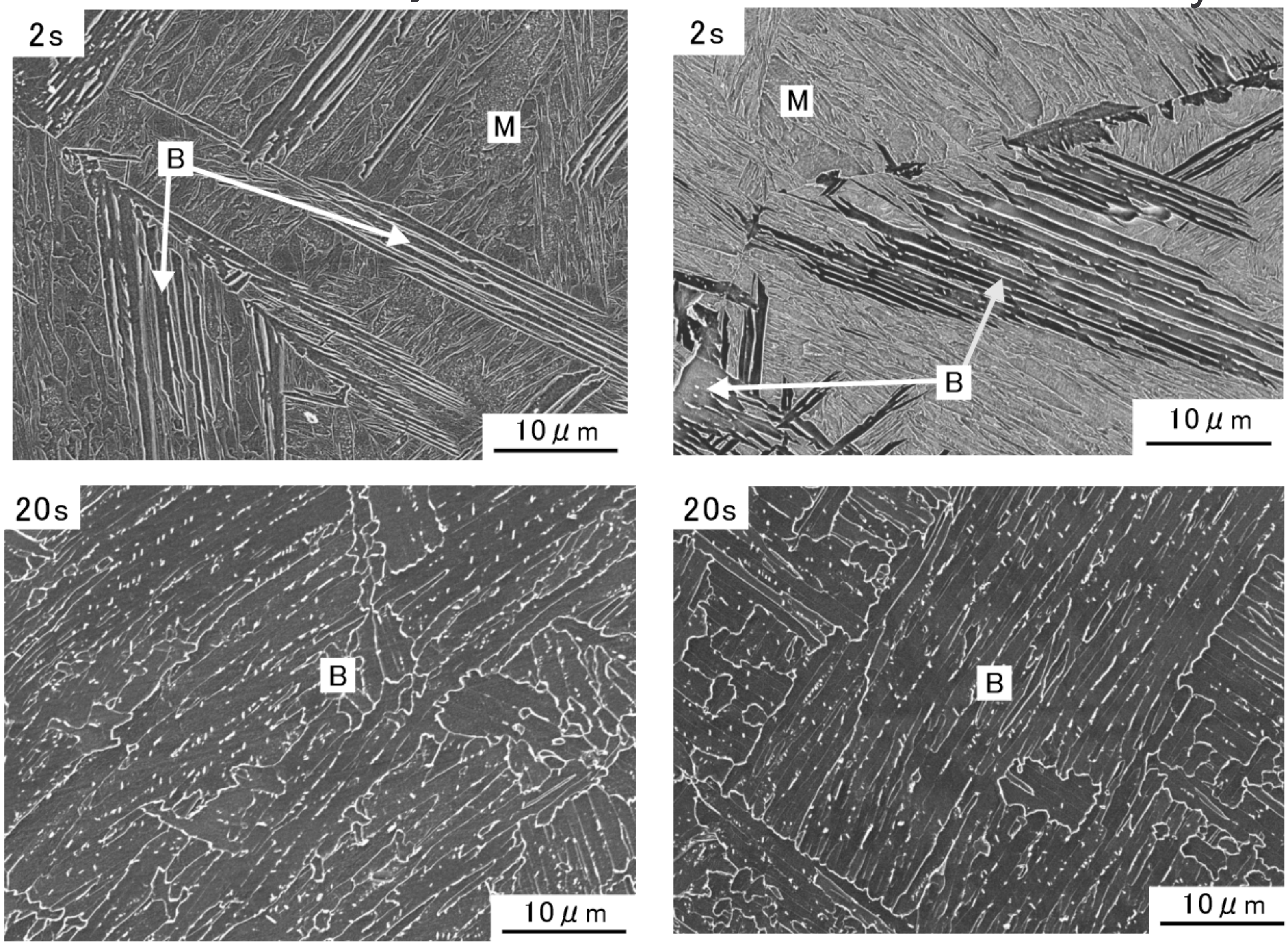


No difference with Nb addition

Fe-0.15C-1.5Mn-(0, 0.03Nb), transformed at 773K (SEM)

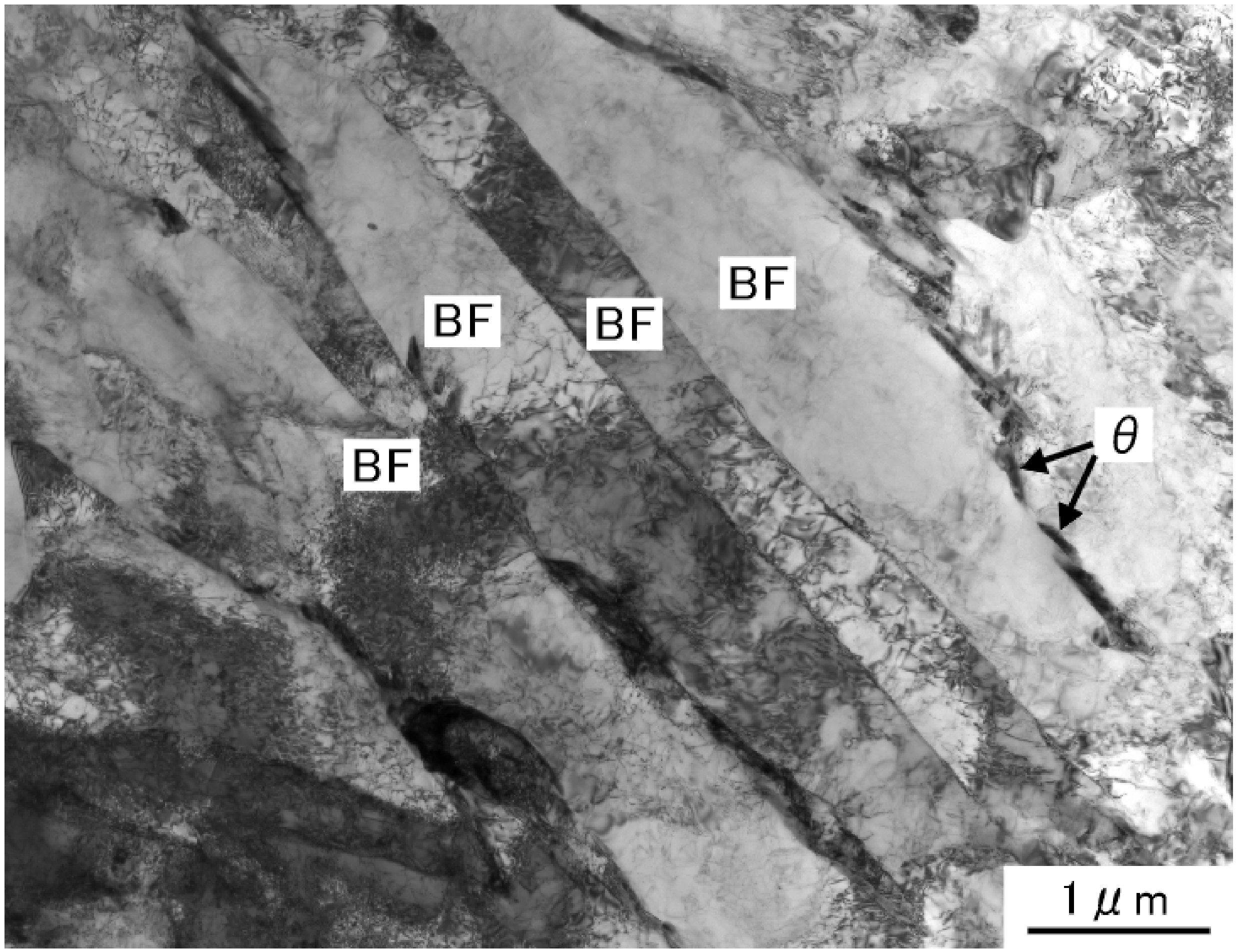
B : Bainite M : Lath martensite

Nb free alloy 0.03%Nb added alloy



Fe-0.15C-1.5Mn-0.03Nb transformed at 773K (TEM)

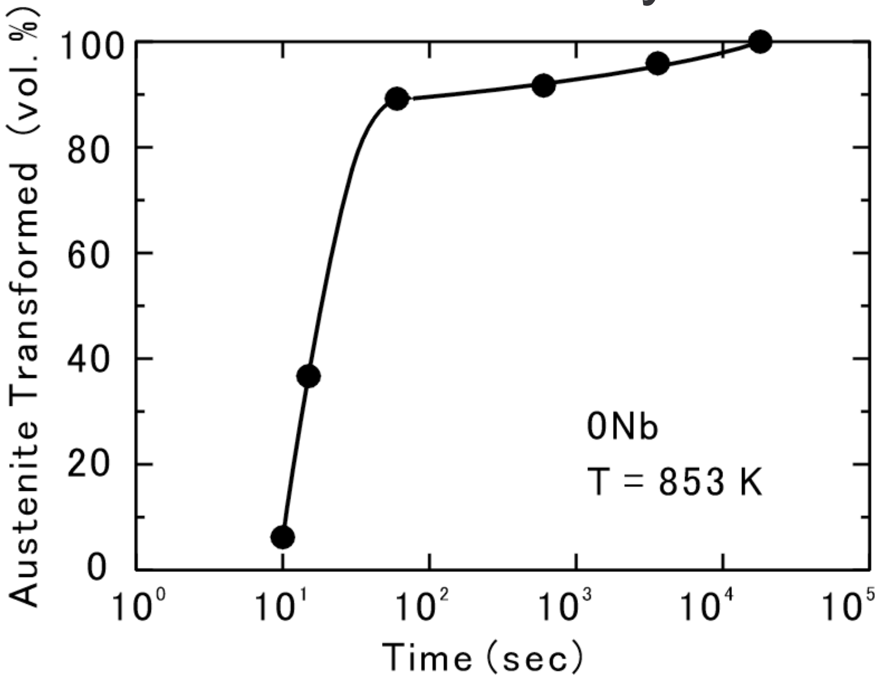
BF : Bainitic Ferrite θ : Cementite



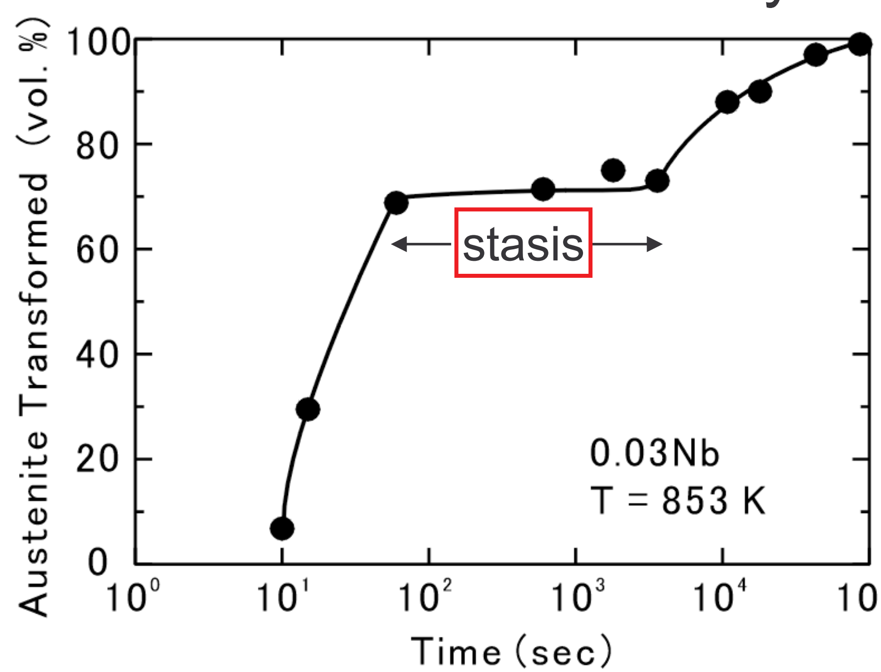
BFs are of the same orientation

Fe-0.15C-1.5Mn-(0, 0.03Nb), transformed at 853K

Nb free alloy



0.03%Nb added alloy

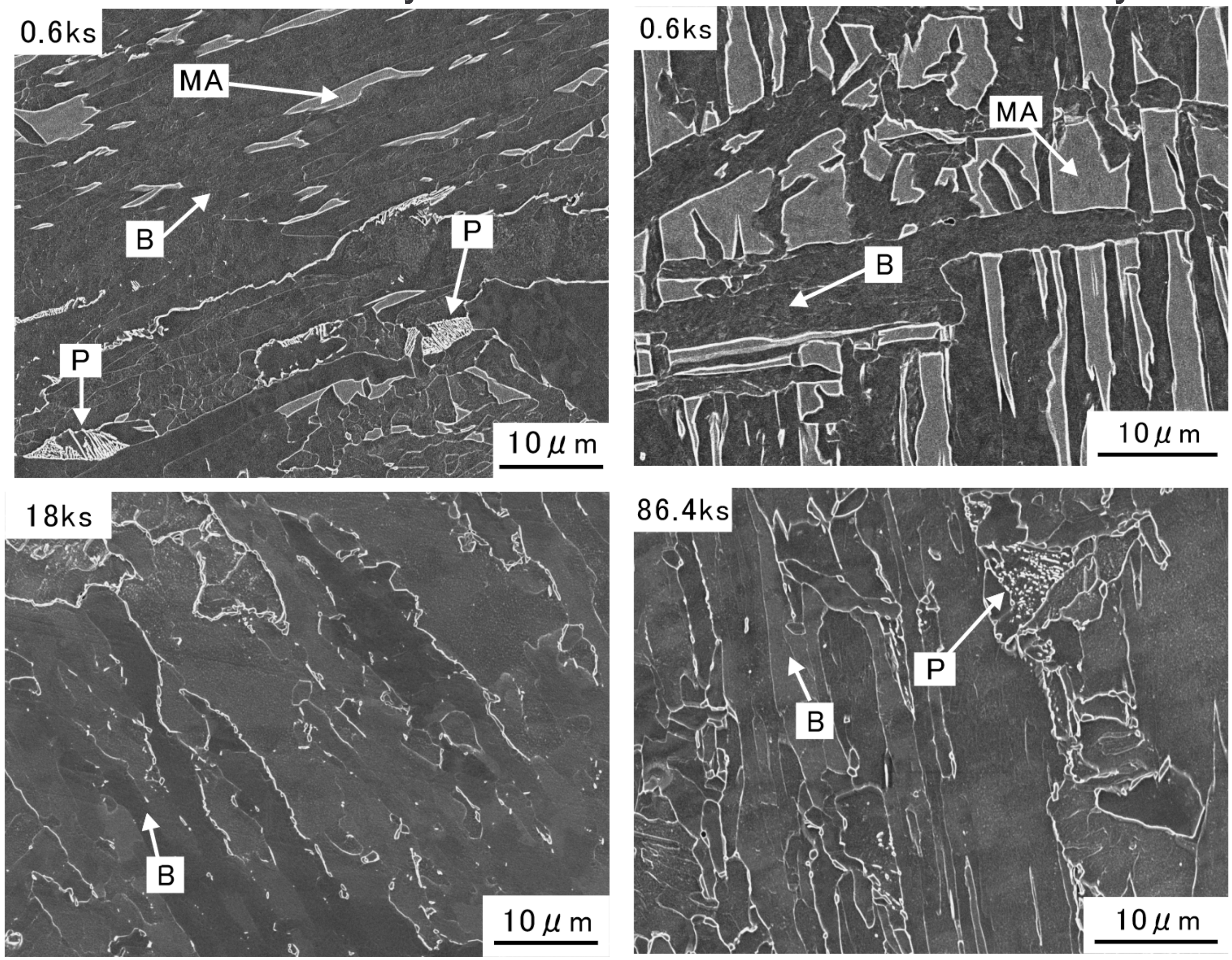


A transformation stasis appears with Nb addition.

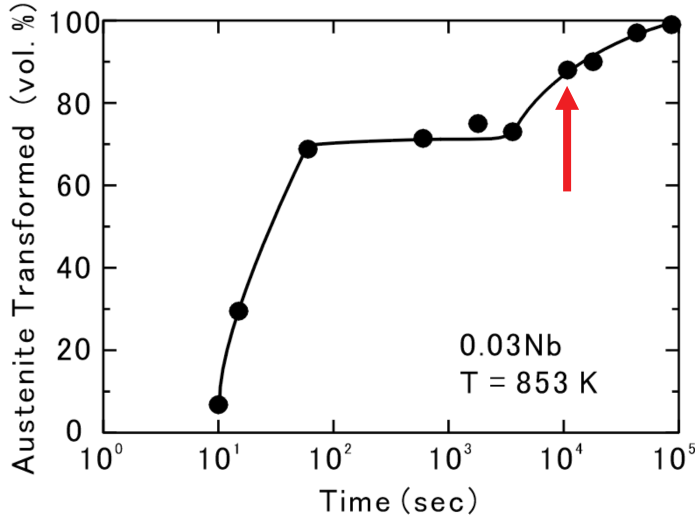
Fe-0.15C-1.5Mn-(0, 0.03)Nb, transformed at 853K (SEM)

P : Pearlite　B : Bainite　MA : Martensite-Austenite constituent

Nb free alloy　　　　0.03%Nb added alloy

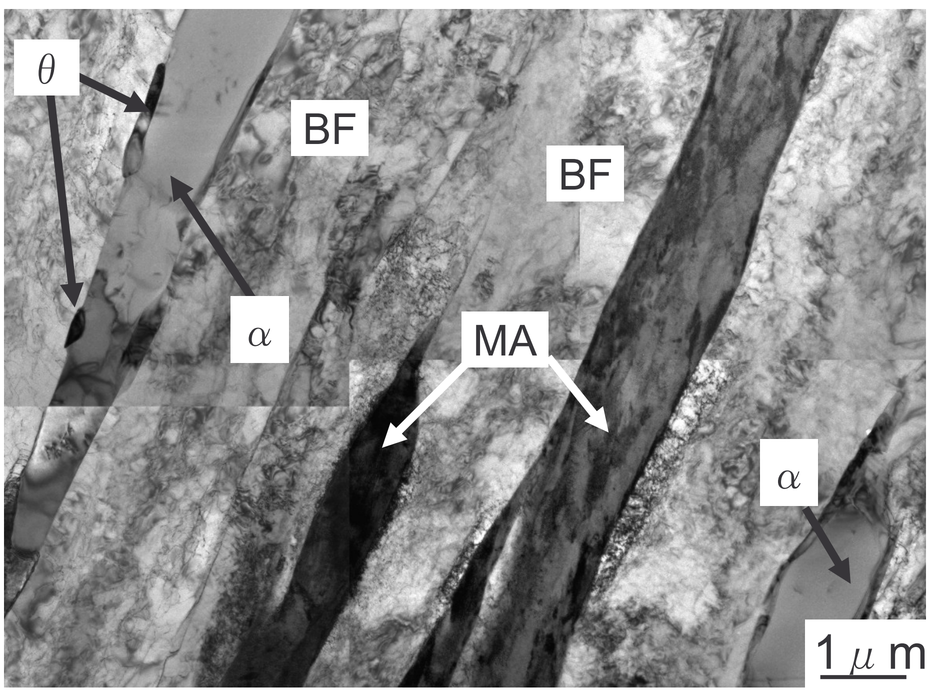


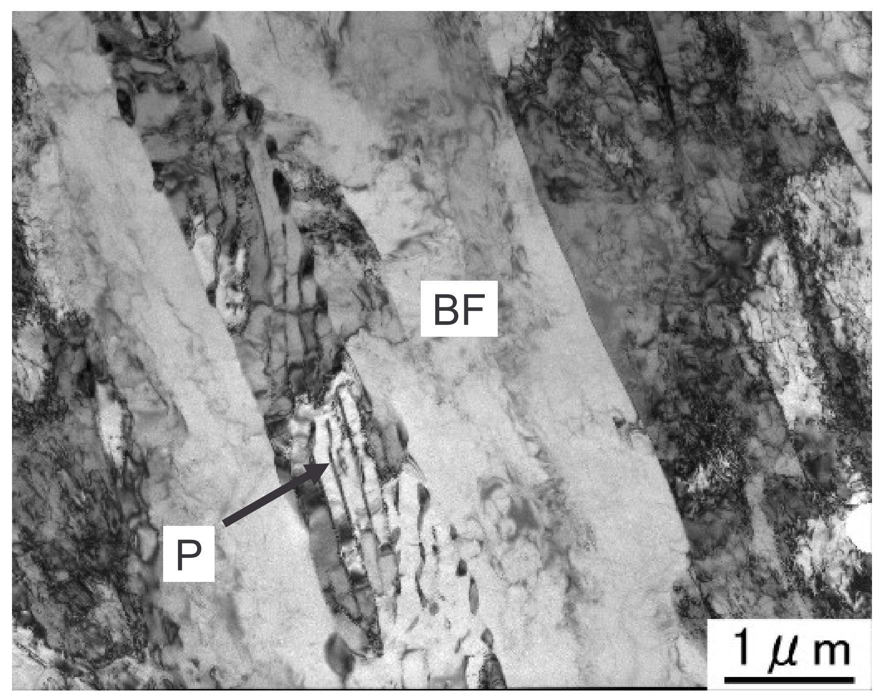
Fe-0.15C-1.5Mn-0.03Nb transformed at 853K for 10.8ks (TEM)



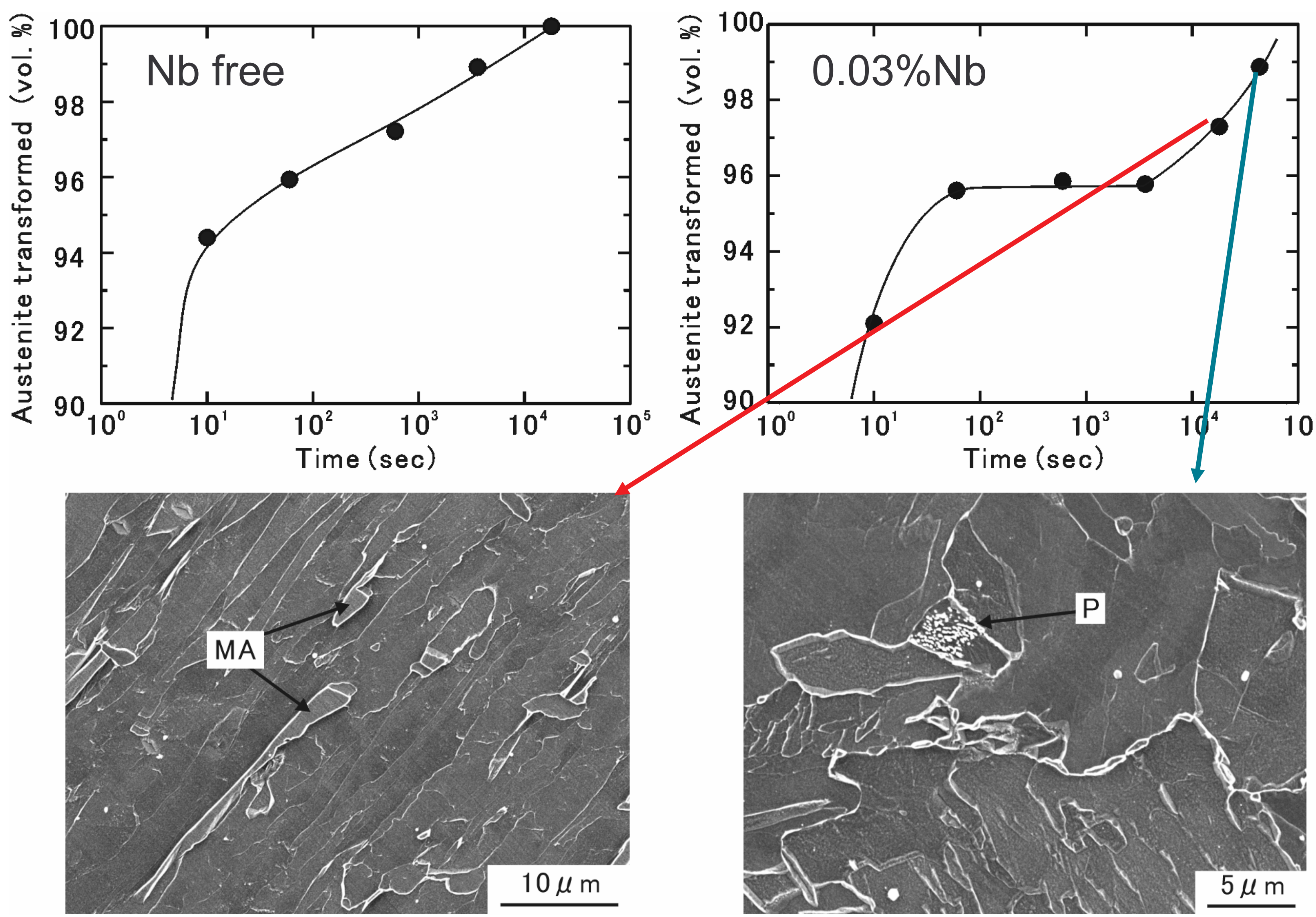
BF : Bainitic Ferrite P :Pearlite
α : Ferrite θ : Cementite
MA :Martensite-Austenite constituent

Dislocation-free ferrites of new orientations containing θ forms after the statis.

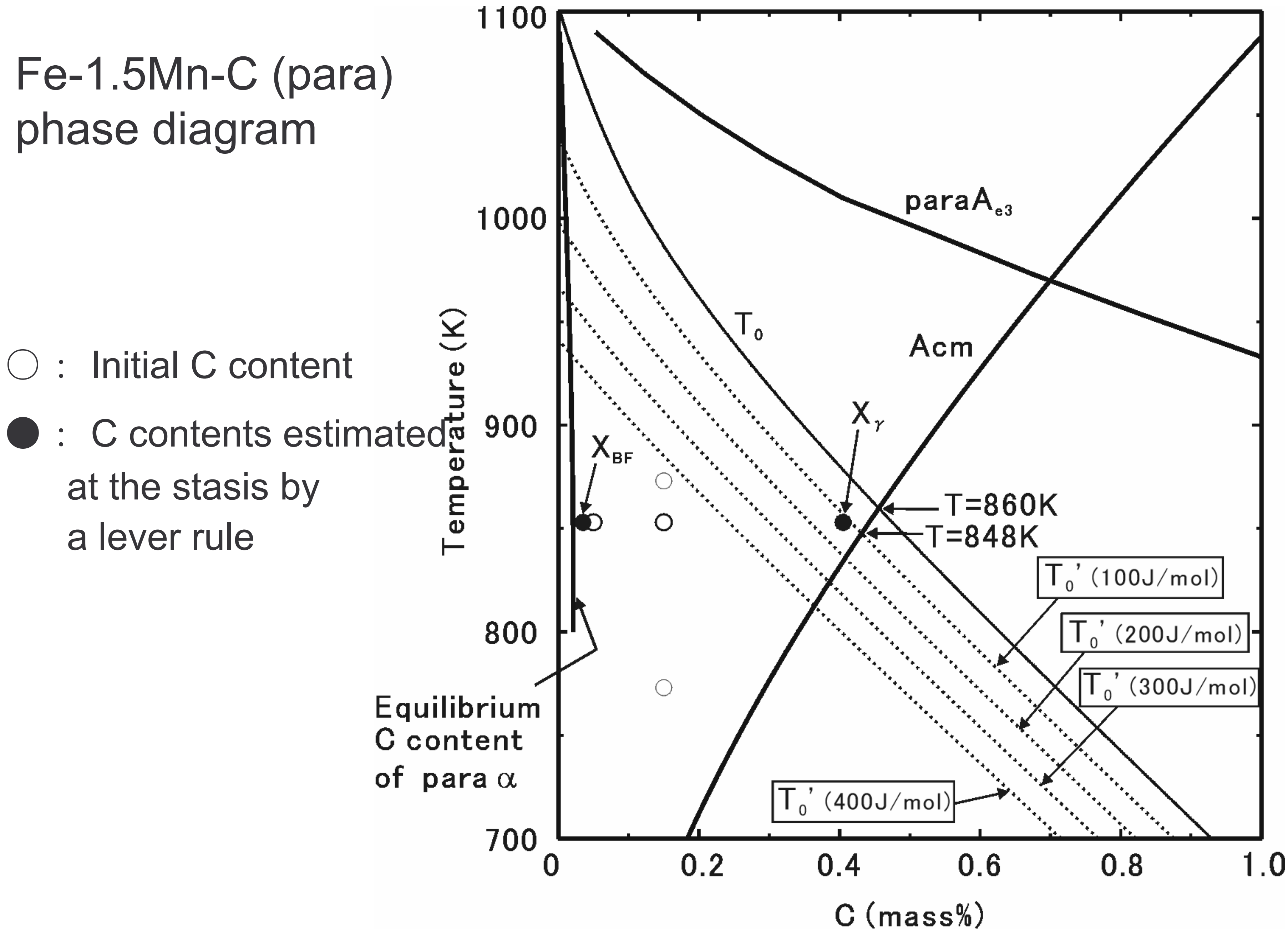




Fe-0.05C-1.5Mn alloys transformed at 853K



Fe-1.5Mn-C (para) phase diagram

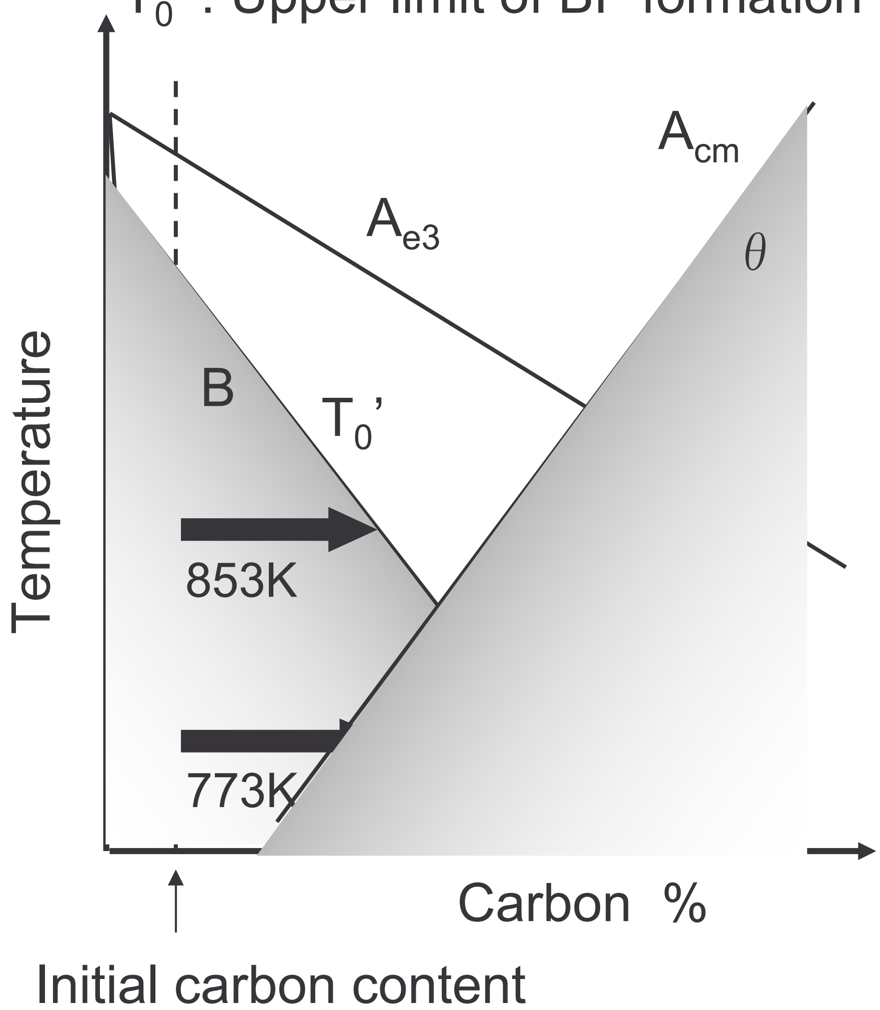


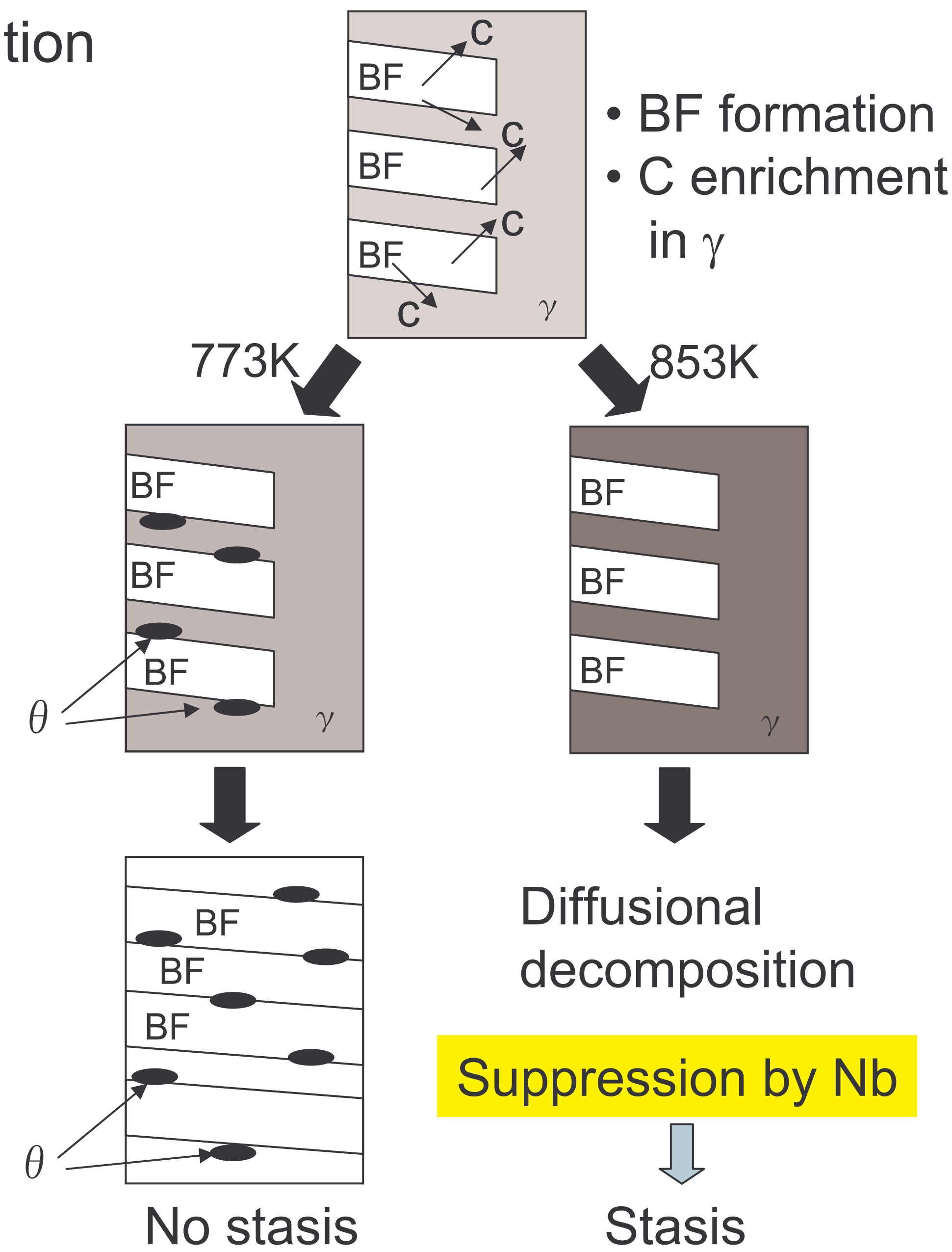
Possible machanism for transformation stasis with Nb addition

773K : No differnce with Nb addition

853K : Stasis with Nb addition

T_0' : Upper limit of BF formation





Suppression of ferrite transformation with Nb addition

On nucleation

Decrease in γ grain bounday energy with Nb segregation

(M. Enomoto, N. Nojiri, Y. Sato : Mater. Trans., JIM, 35 (1994), 859)

Decrease in BF/γ bounday energy with Nb segregation

On growth

Solute drag effect by Nb

(M. Suehiro, Z. -K. Liu, J. Ågren : Acta Mater., 44 (1996), 4241)

Decrease in diffusion coefficient of carbon

(S. Nanba, H. Morimoto, G. Anami, T. Towada:
Kobe steel Eng. Rep., 47 (1997), 8)

Pinning by Nb(C,N) precipitation

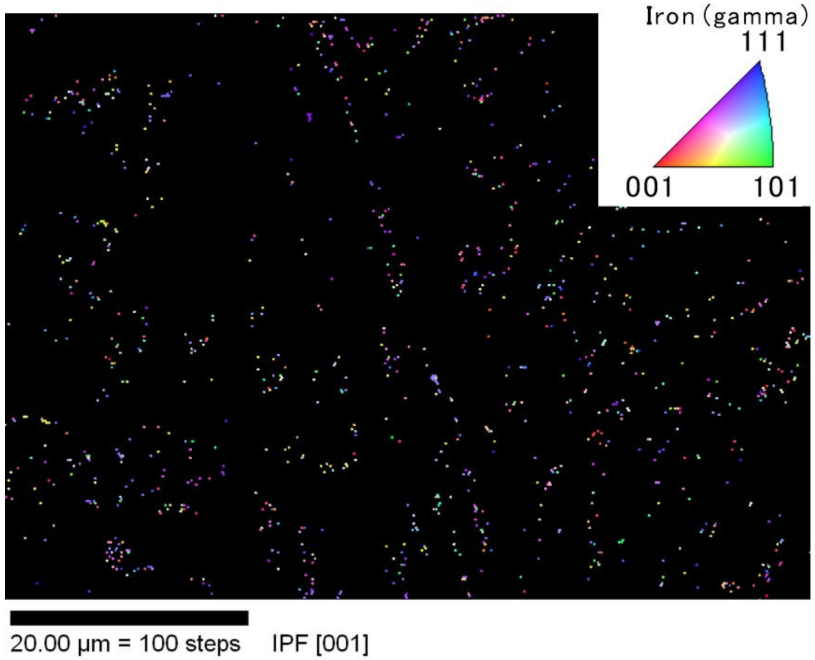
(Summary)

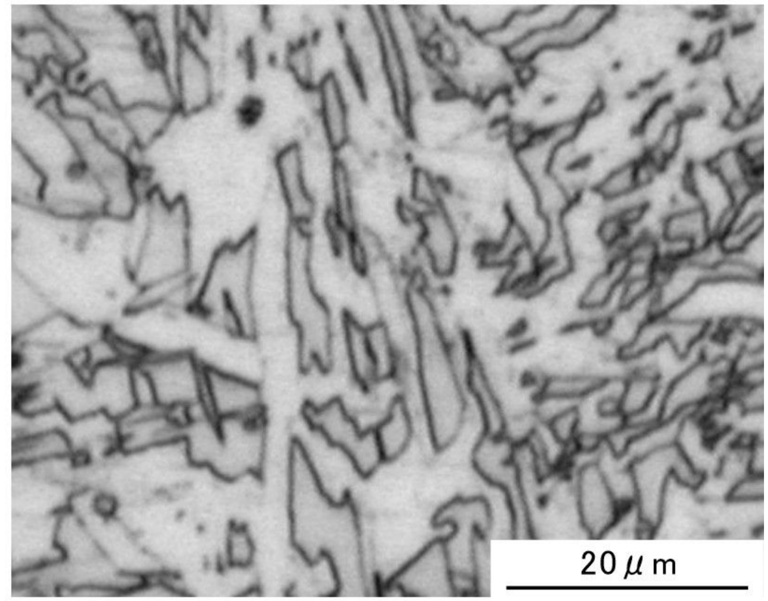
1. A transformation stasis in upper bainite transformation appears in Mn-containing HSLA steels microalloyed with Nb.

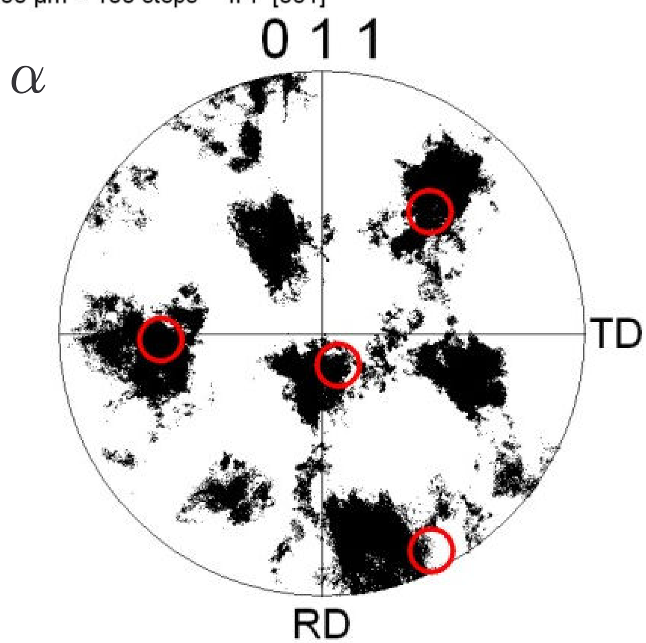
2. Dislocation-free ferrites of which orientations are different from those of adjacent BFs form with cementite precipitation after the stasis.

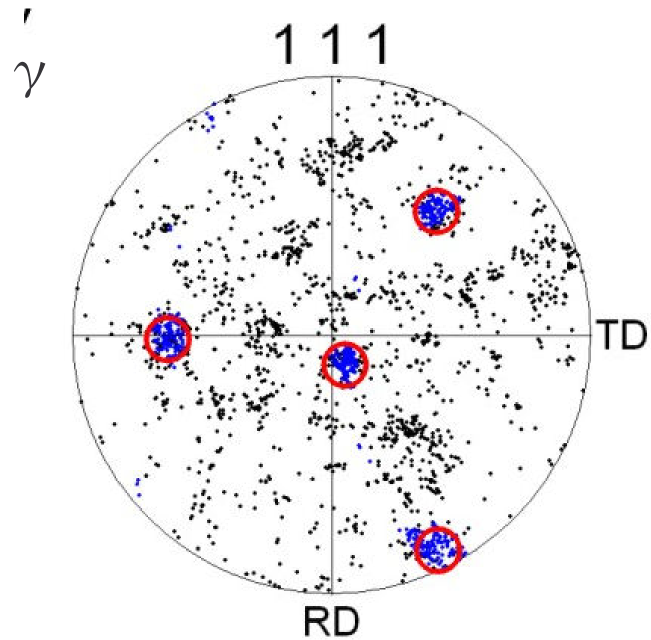
3. Nb may suppress the nucleation of ferrite at BF/γ interphase boundary in a temperature range where an incomplete transformation is expected for bainite.

γ orientation mapping by EBSD





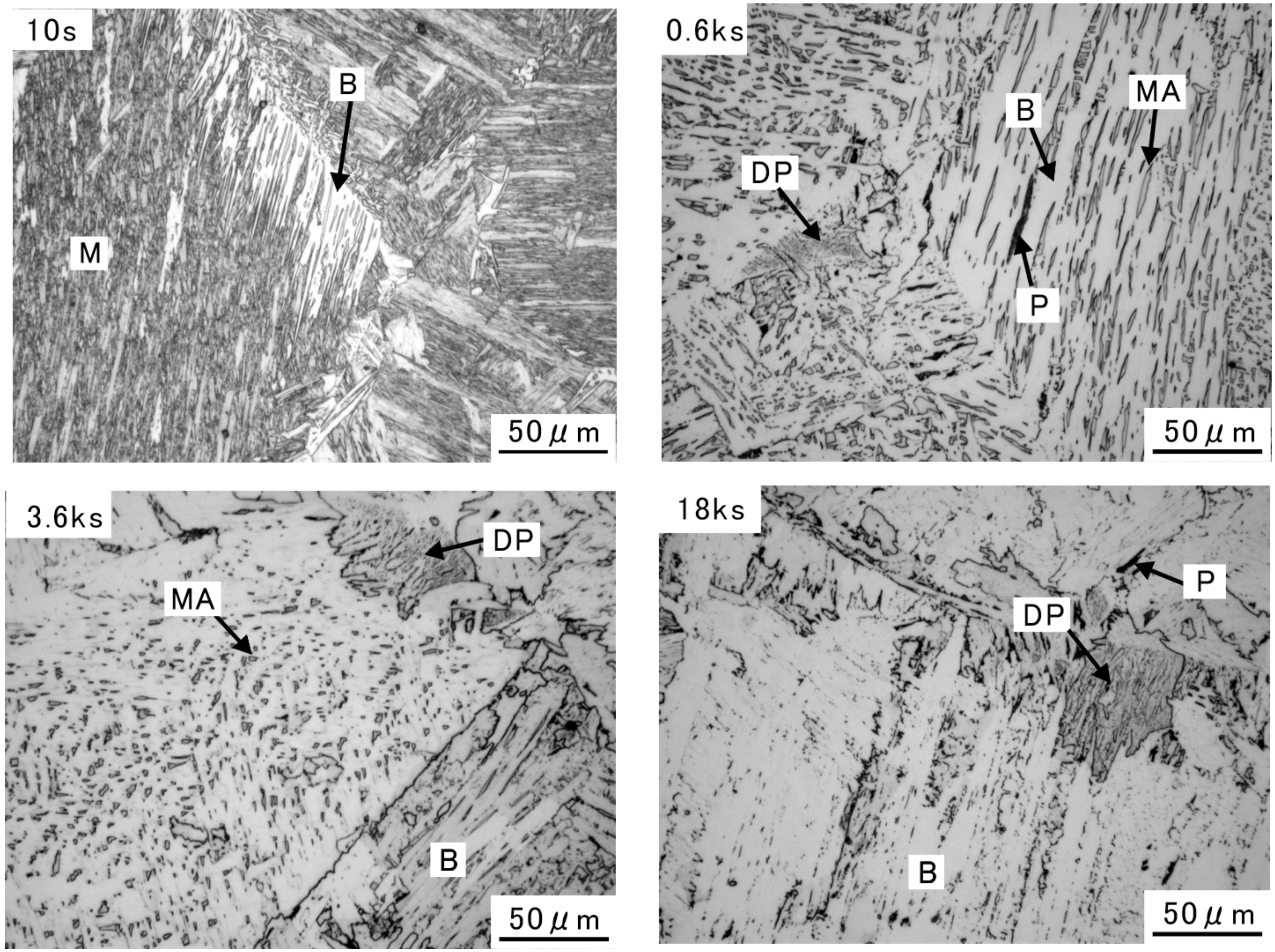




Nb-free Fe-0.15C-1.5Mn, transformed at 853K (OM)

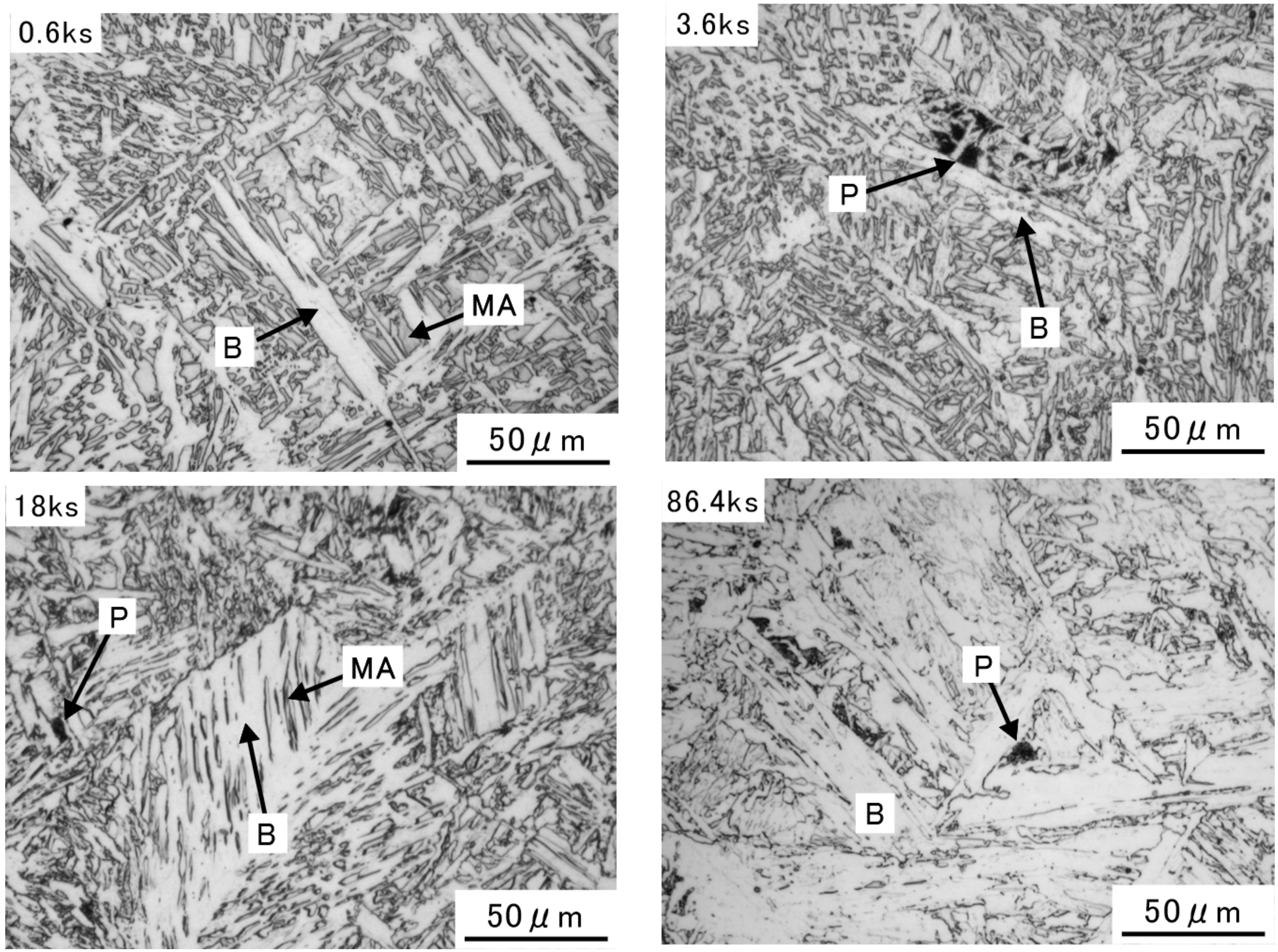
P :Pearlite   DP : Degenerate Pearlite B : Bainite

M : Lath MartensiteMA :Martensite-Austenite constituent

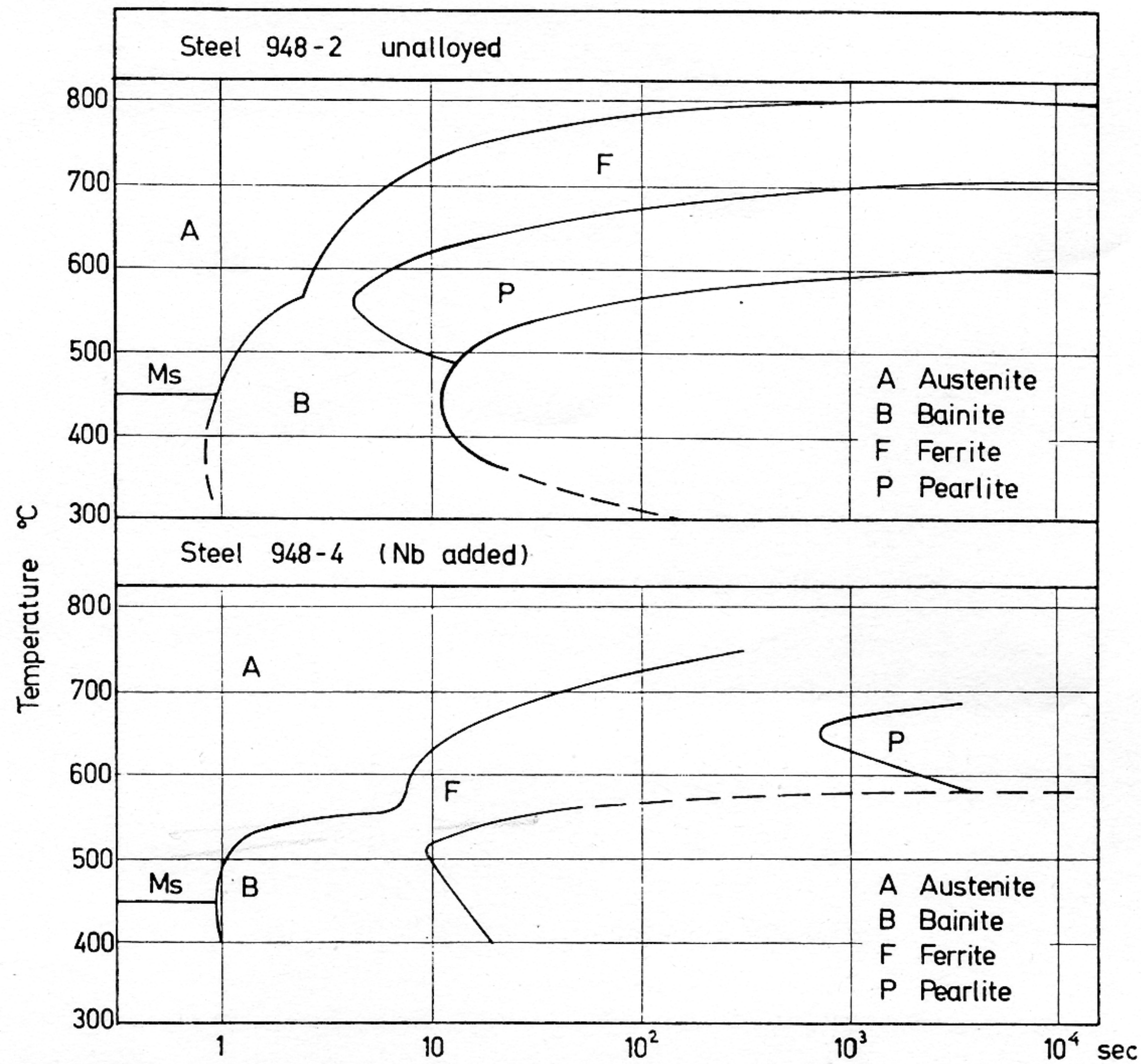


Fe-0.15C-1.5Mn-0.03Nb, transformed at 853K (OM)

P :Pearlite B : Bainite MA :Martensite-Austenite constituent



Fe-0.11C-1.01Mn (mass%)

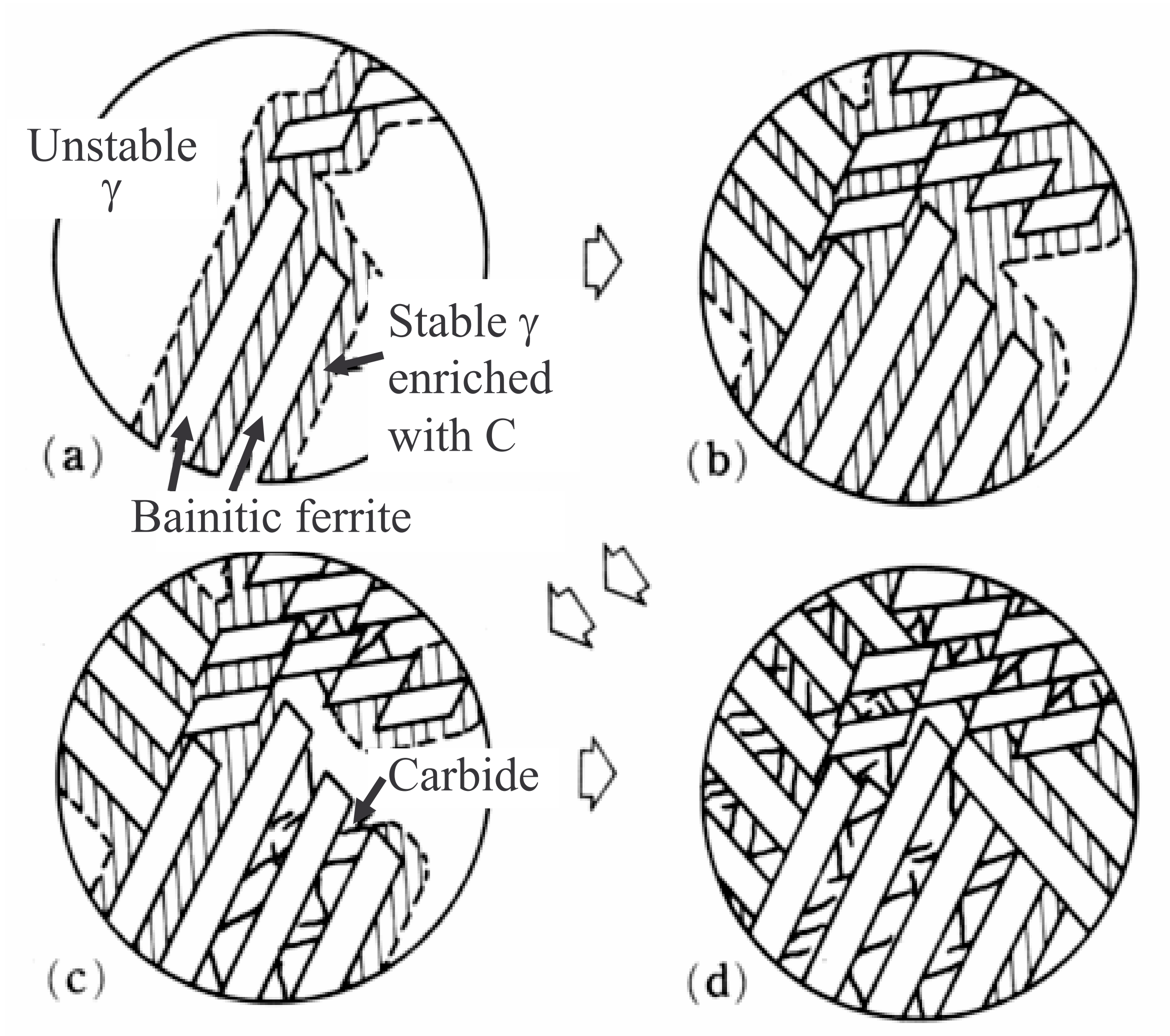


(F. De Kazinczy et al. Jernkont. Ann. 147 (1963), 4)

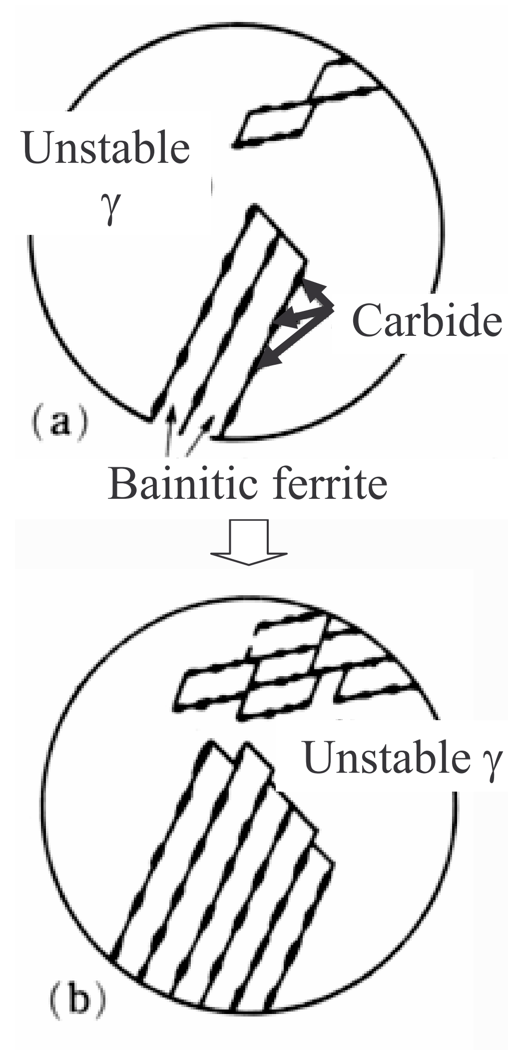
Si containing alloys (medium carbon steel for spring, low carbon TRIP steel)

Suppression of cementite precipitation in γ

→ Increase in retained γ



Carbon steel



Solute Drag Effect

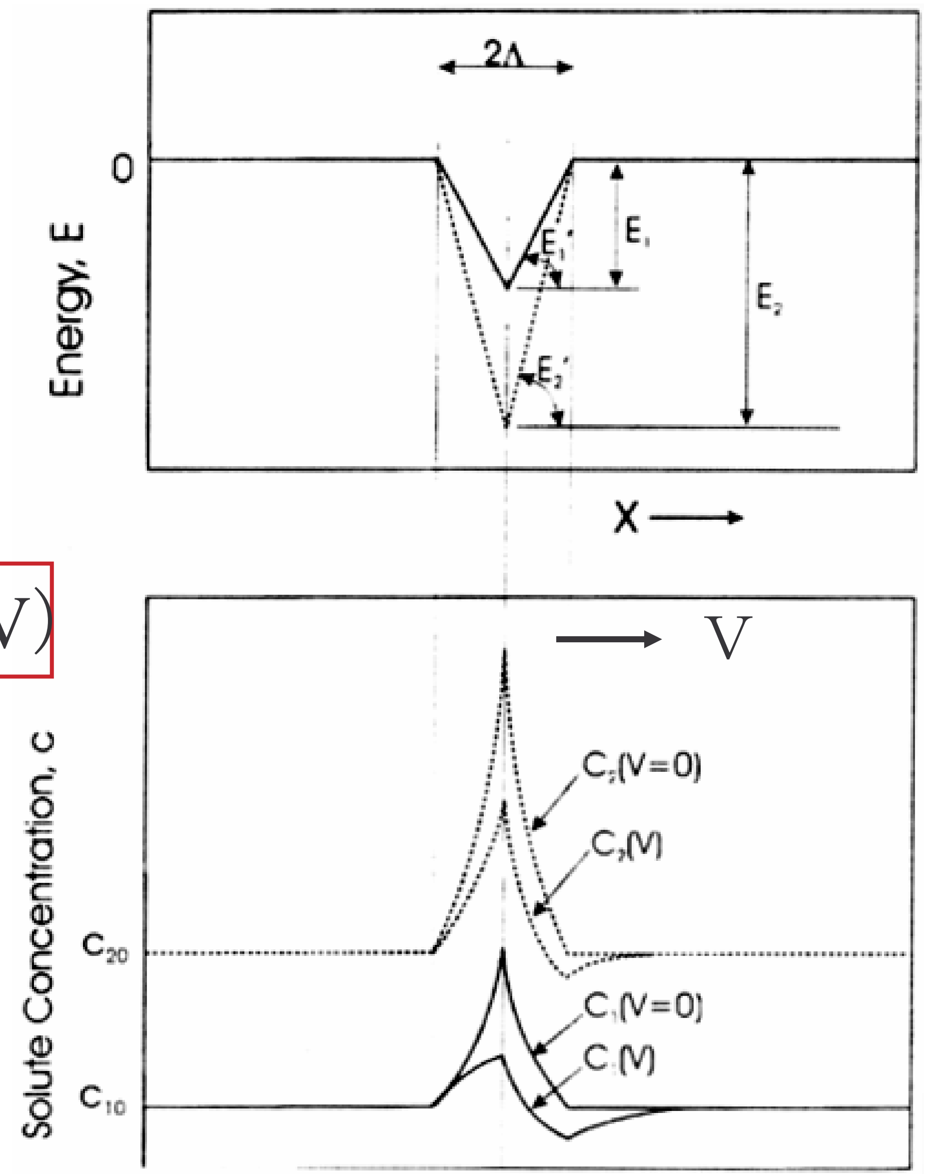
Segregation of alloying element on α/γ interface

↓

Decrease in growth rate (V)

$$\frac{V}{M} = \frac{\Delta G}{V_m} - P$$

P → drag force



Purdy, Brechet: Acta Metall. Mater., 1995

Effect of Nb addition on C diffusion

Diffusion of carbon in γ

$$D_C = m_C RT \cdot \left[1 + x_C^\gamma \cdot \frac{\partial \ln \gamma_C^\gamma}{\partial x_C^\gamma} \right]$$

m_c : mobility   R : gas constant

T : temperature

x_c^γ : carbon content in γ

γ_c^γ : activity coefficient of carbon in γ

↓ *Regular solution approximation*

$$D_C \approx m_C RT \left(1 - x_C^\gamma \frac{2\Omega_{FeC}^\gamma + W_{MC}^\gamma \cdot x_M^\gamma}{RT} \right)$$

Ω_{FeC}^γ : Fe-C interaction parameter in γ

W_{MC}^γ : M-C interaction parameter in γ

(T. Nishizawa : Bull. Jpn. Inst. Met., 12(1973), 401)

$$2\Omega_{FeC}^\gamma \sim -25000 \ cal / mol$$
$$W_{NbC}^\gamma \sim -145722 \ cal / mol$$
$$x_{Nb}^\gamma < 0.0002$$

$$\left| 2\Omega_{FeC}^\gamma \right| >> \left| W_{NbC}^\gamma \cdot x_{Nb}^\gamma \right|$$