The 155th ISIJ meeting (2008.3.28)
International organized session
"Effects of alloying elements on microstructure formation in steels and other materials"

Incomplete transformation of bainite in microalloyed high strength low alloy steels

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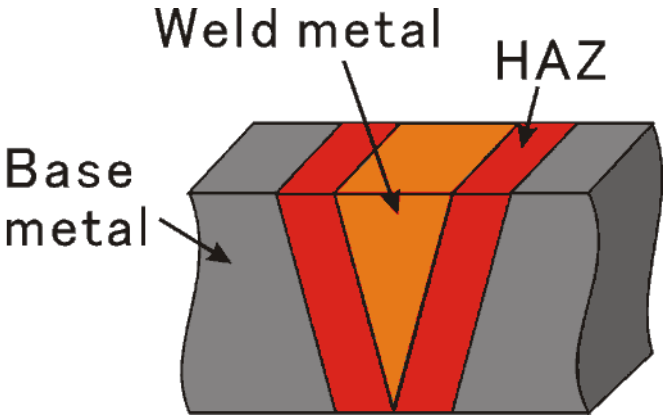
Industrial importance of bainitic steel - example

Welded structural steels ***e.g., Bridge, Building, Vessel, Pipeline etc.***



Transformation during fast cooling from coarse γ grains

Formation of Martensite/Austenite (MA) constituent

⇩

Degradation of toughness

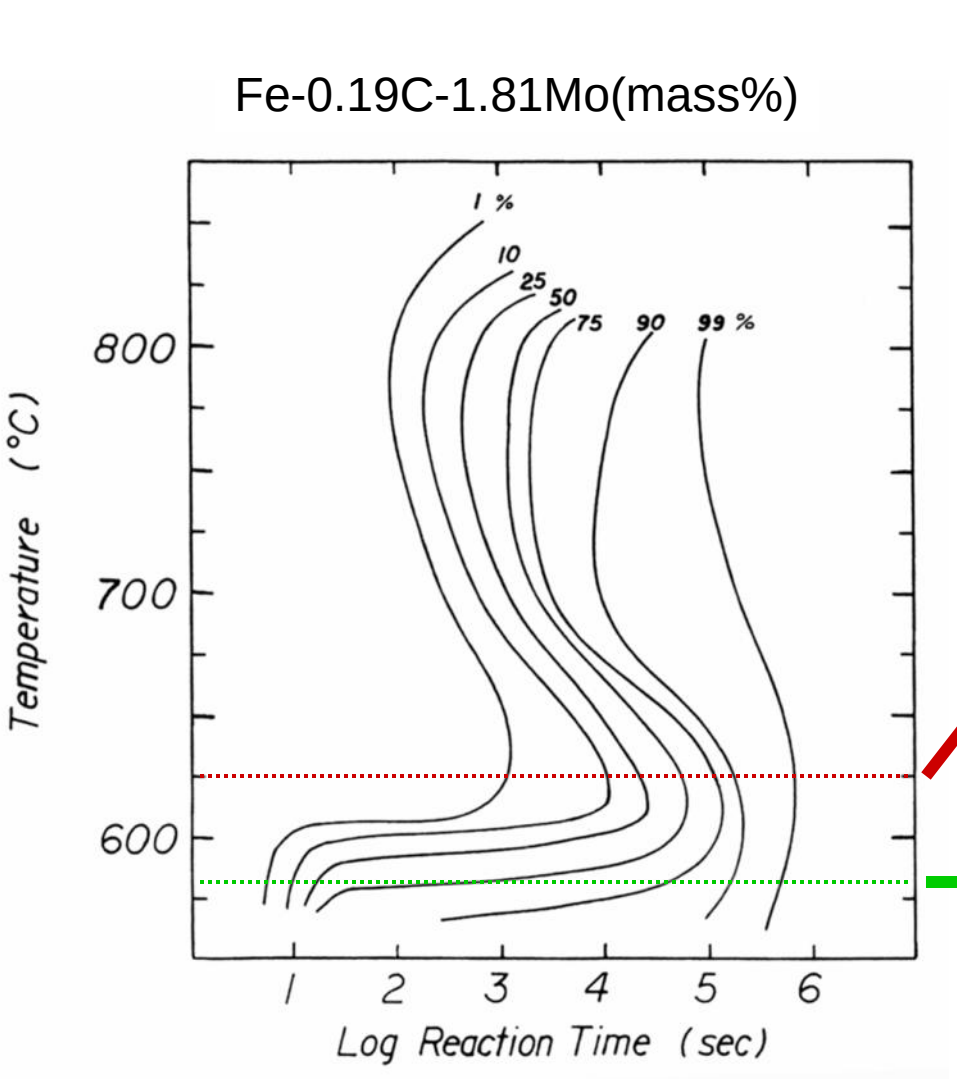
- Decrease in carbon content down to less than 0.1mass% for better weldability
- Use of bainitic structure to obtain high strength

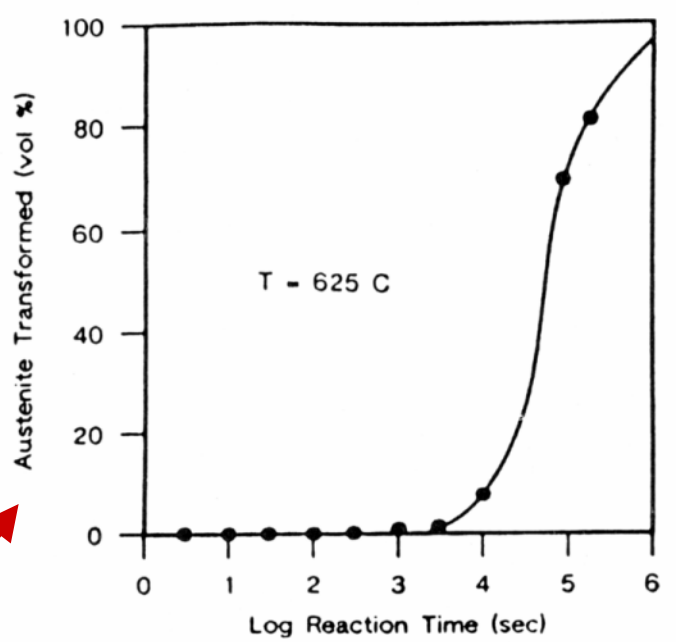
Microalloying (B, Mo, Nb) for increasing in hardenability

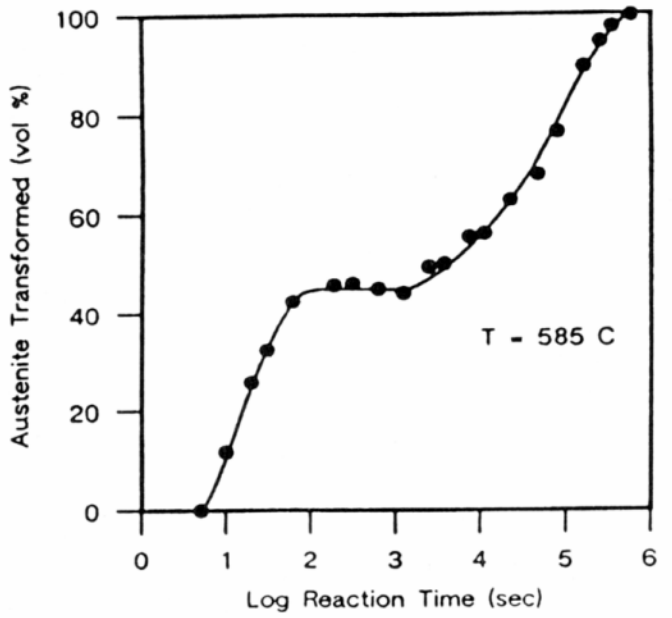
⇩ but increase in the amount of MA

Nb bearing steel - *Incomplete transformation of bainite*

Transformation stasis (Incomplete transformation)



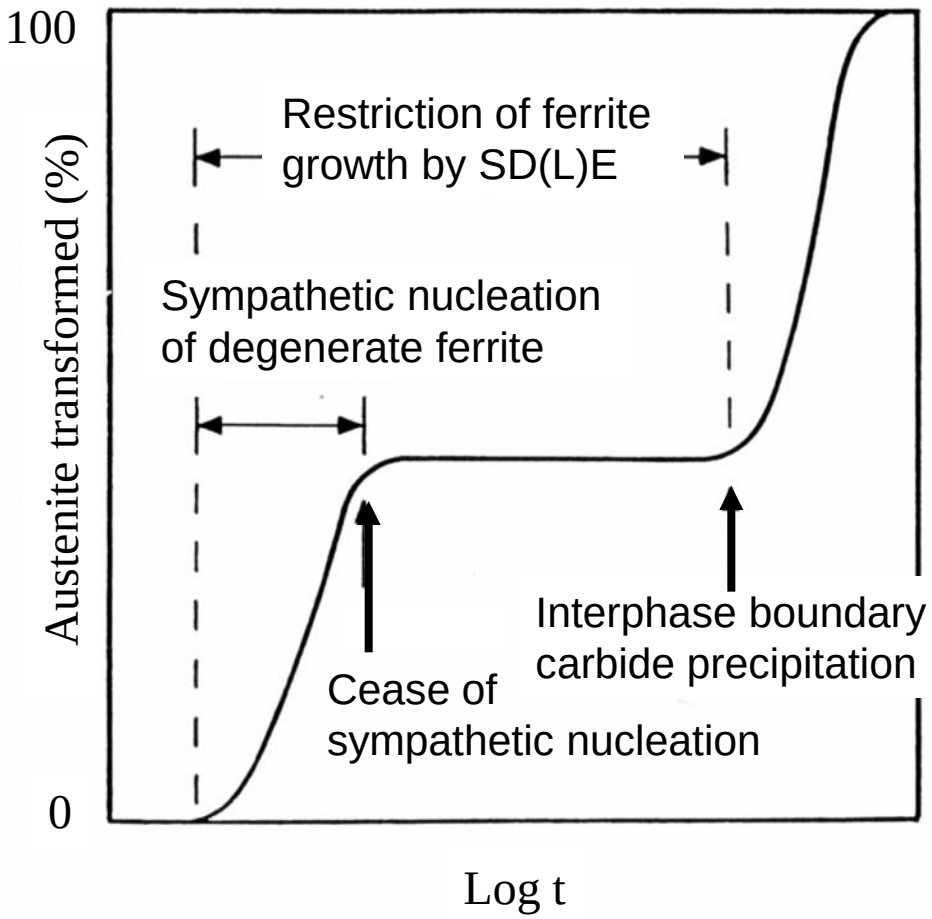




Reynolds, Li, Shui, Aaronson : Met. Trans. A. 1990

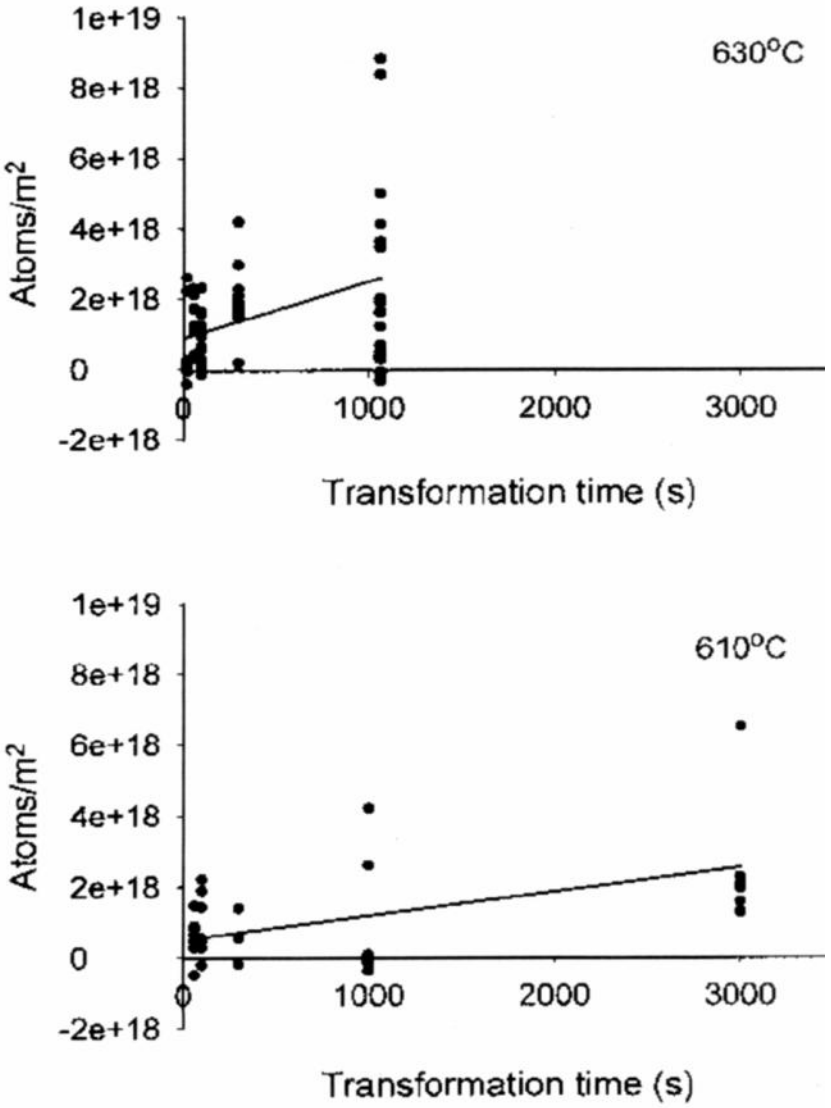
Explanation of the transformation stasis below the bay by SD(L)E

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



Mo segregation at γ/α interface

(Humphery et al: MMTA, 2004.)



Bainite transformation in Si-added steels

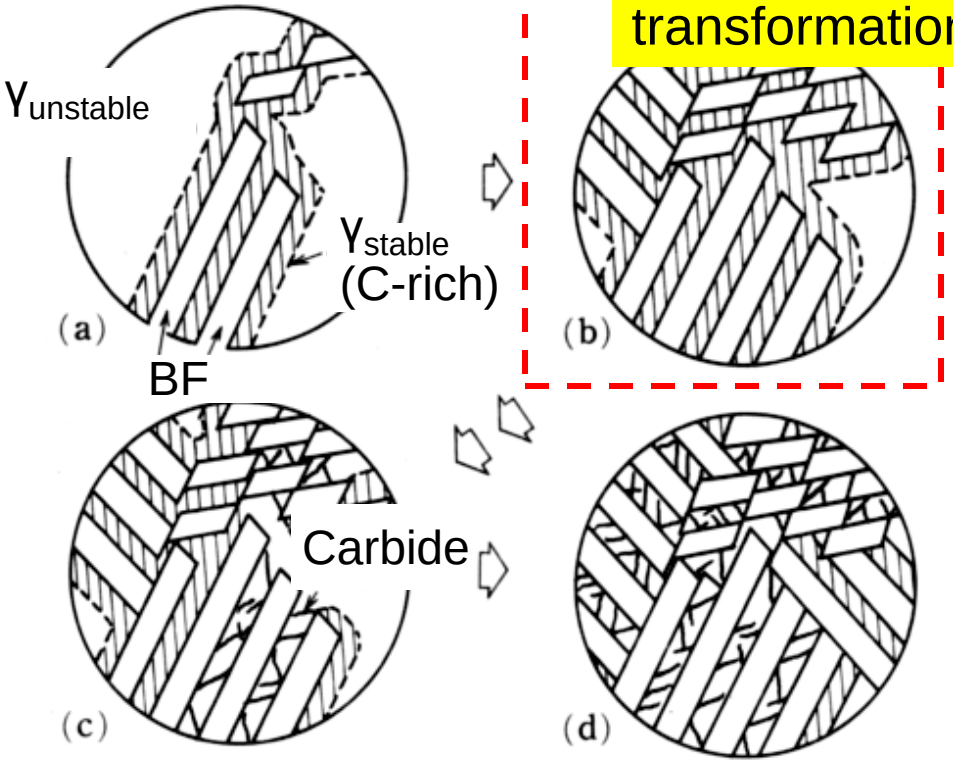
Suppression of Fe_3C precipitation in γ

→ Enrichment of carbon in γ

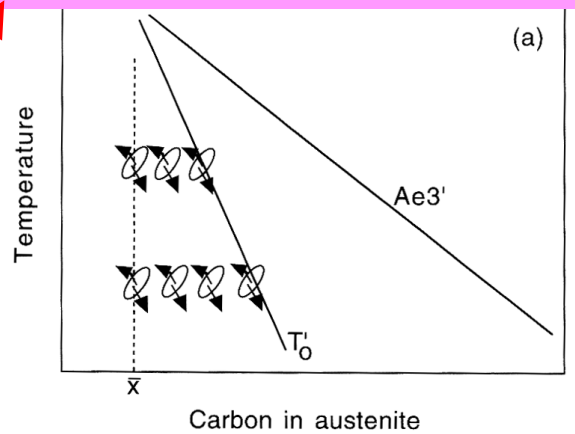
Increase of retained γ ⇨ *TRIP*

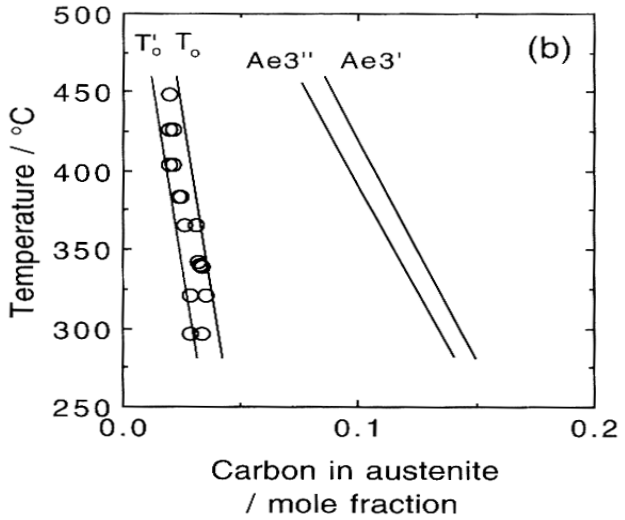
Enrichment of carbon up to T_0' → Loss of driving force for displacive transformation

Incomplete transformation



（Tsuzaki, Maki: Netsushori, **32**(1992), 70.）





Bhadeshia, Edmonds:
Met. Trans., 10A(1979), 895.

(Objective)

To clarify effects of microalloying (Nb, Mo, B) on transformation behavior of Fe-low C-1.5Mn steels

(Experimental)

Materials & Heat treatment

Fe-(0.05, 0.15)C-1.5Mn -0.2Si-(0, 0.030)Nb (mass%)

Isothermal holding : 723 ~ 973 K ~86.4ks

Fe-(0.05, 0.15)C-1.5Mn -(0, 0.5)Mo - (0, 0.001)B

Isothermal holding : 773 ~ 873 K ~ 1036.8 ks

Microstructure observation : OM, SEM, TEM

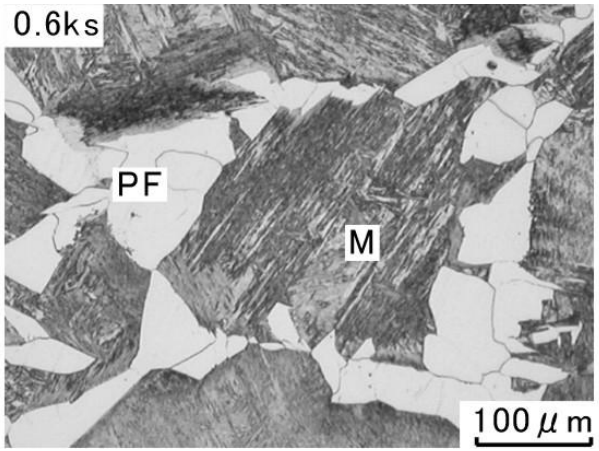
Measurement of phase fraction : Point counting method

Effect of Nb addition

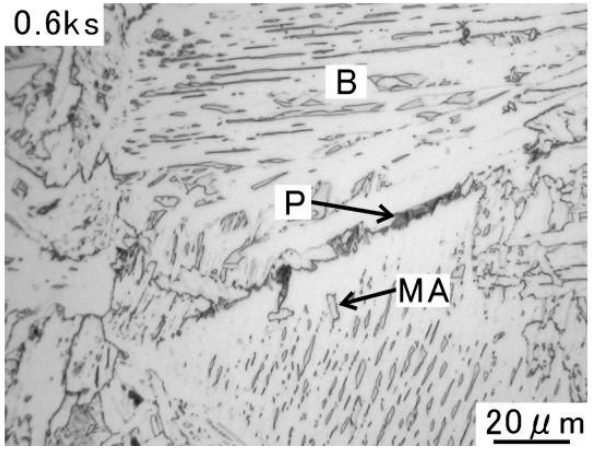
Isothermal transformation (OM)

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

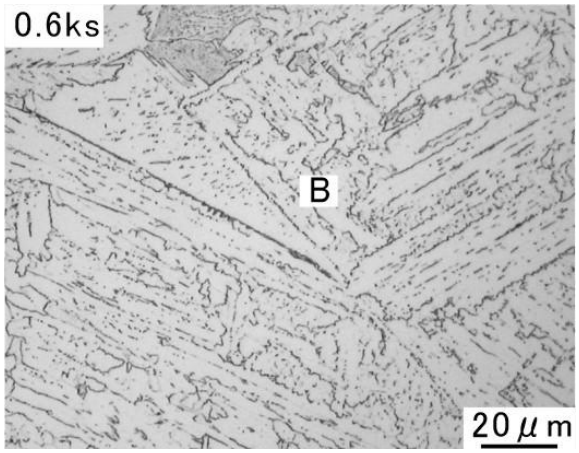
Fe-0.15C-1.5Mn (Nb free alloy)



973K

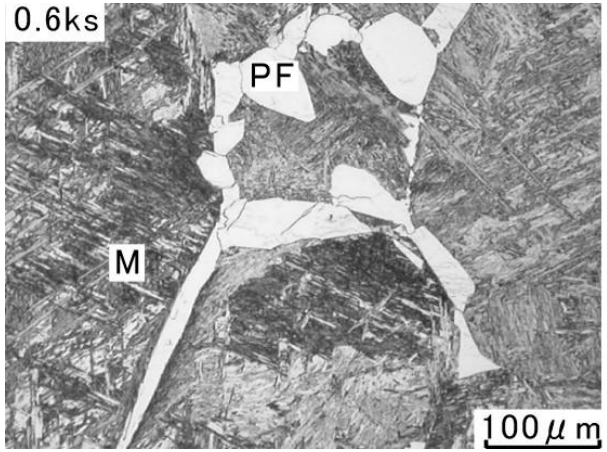


823K

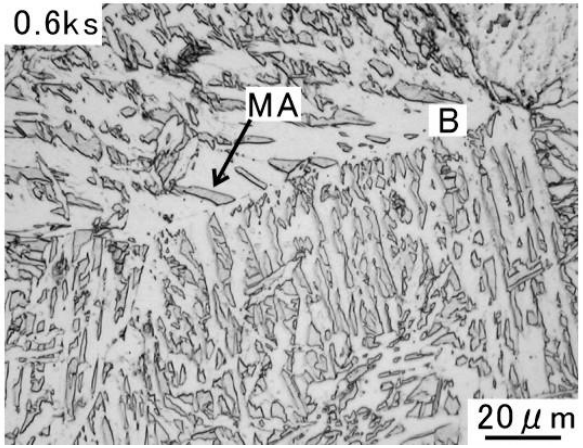


773K

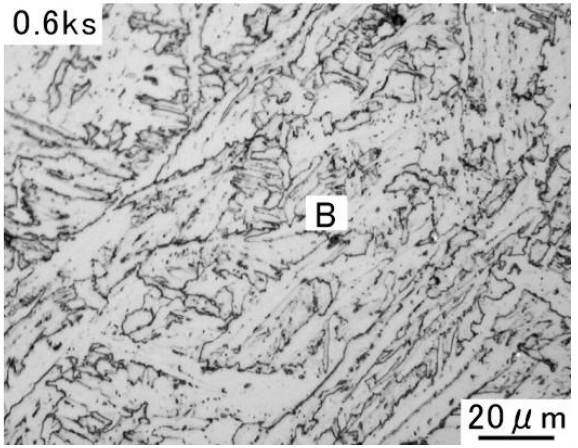
0.03%Nb added alloy



973K

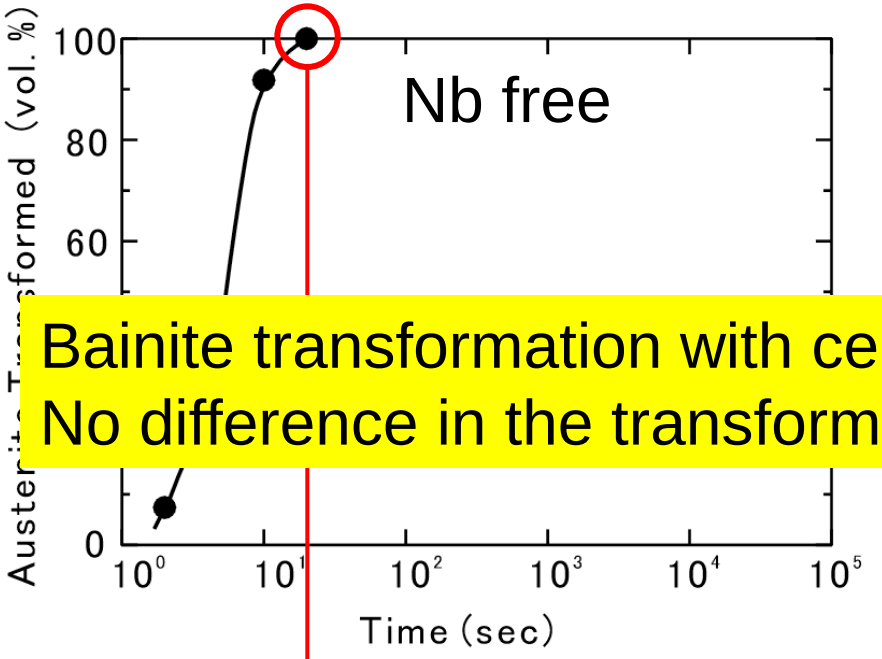


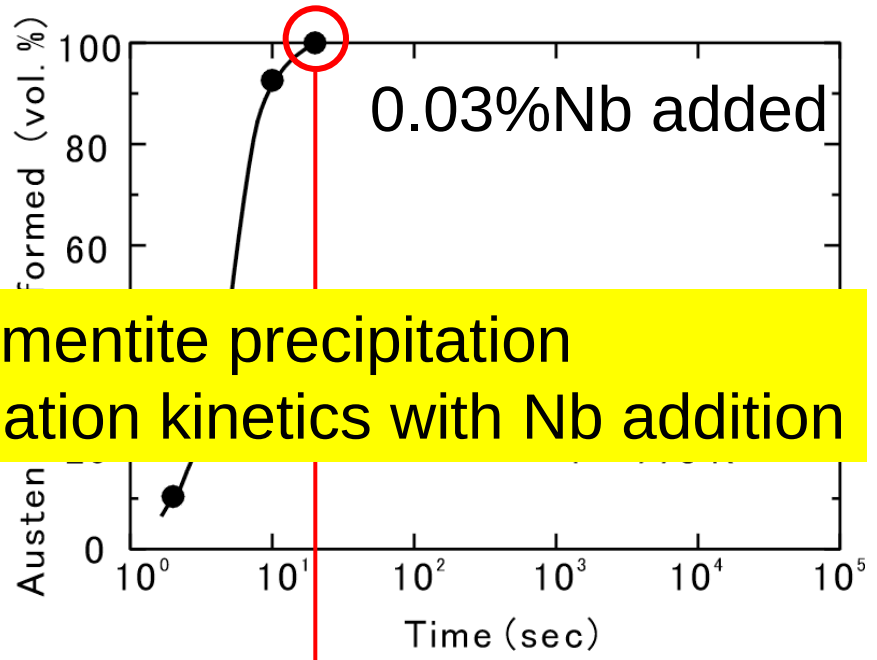
823K



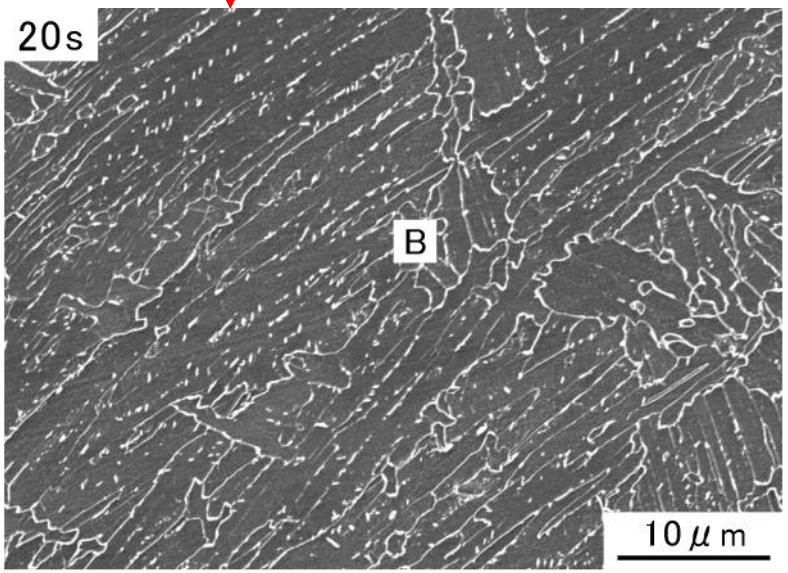
773K

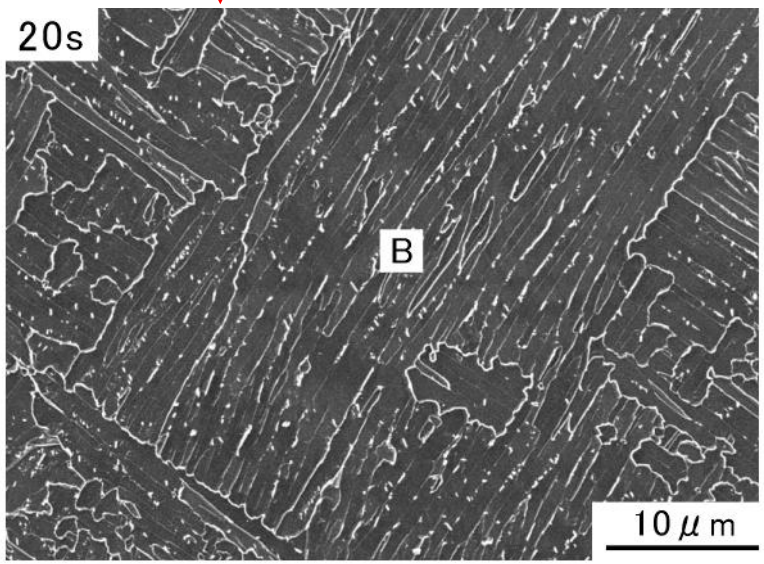
Fe-0.15C-1.5Mn-(0, 0.03Nb) , transformed at 773K



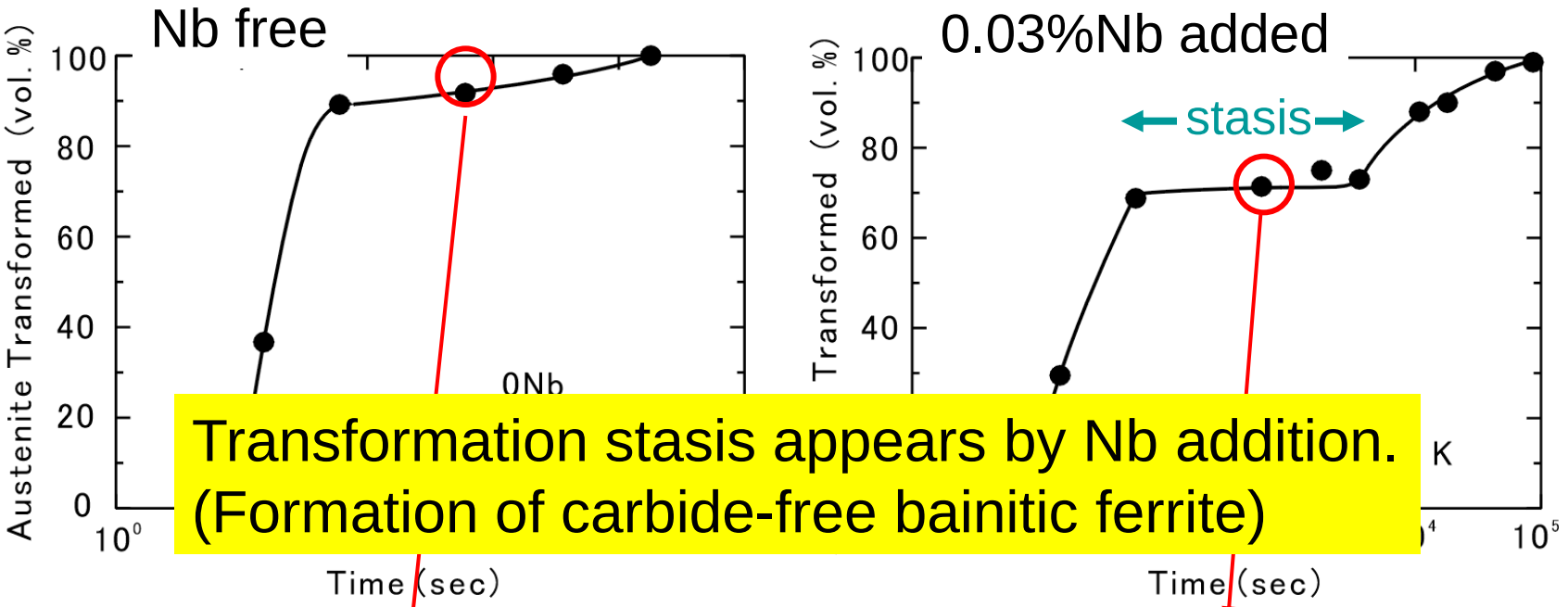


Bainite transformation with cementite precipitation
No difference in the transformation kinetics with Nb addition

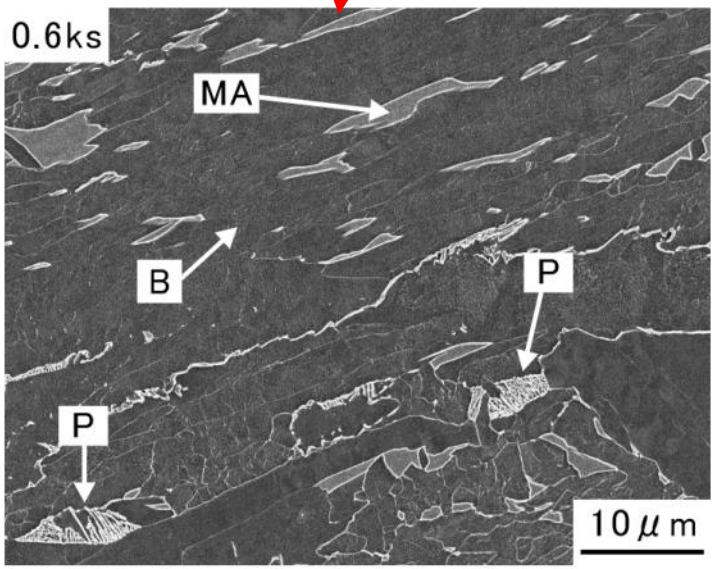


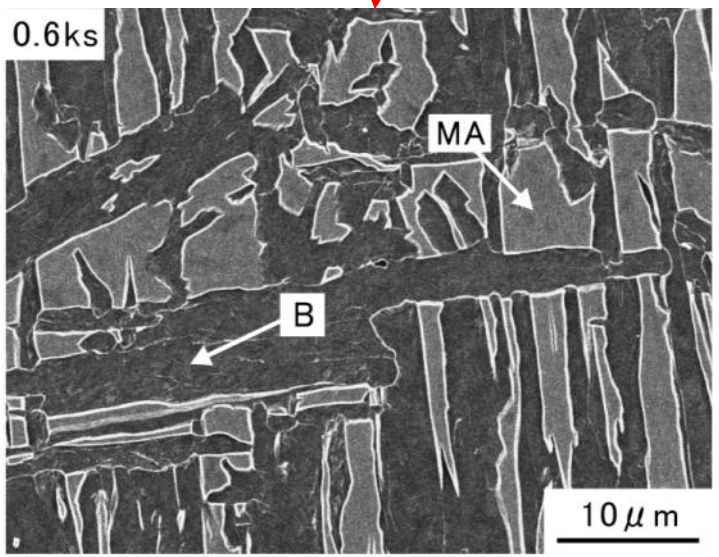


Fe-0.15C-1.5Mn-(0, 0.03Nb), transformed at 853K

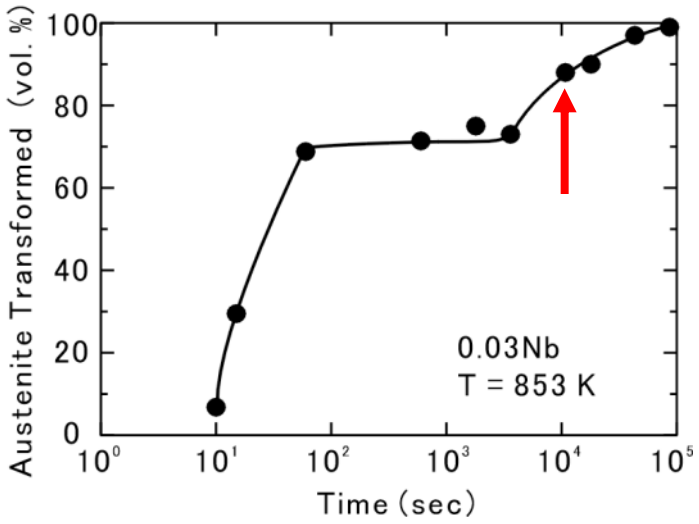


Transformation stasis appears by Nb addition.
(Formation of carbide-free bainitic ferrite)





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

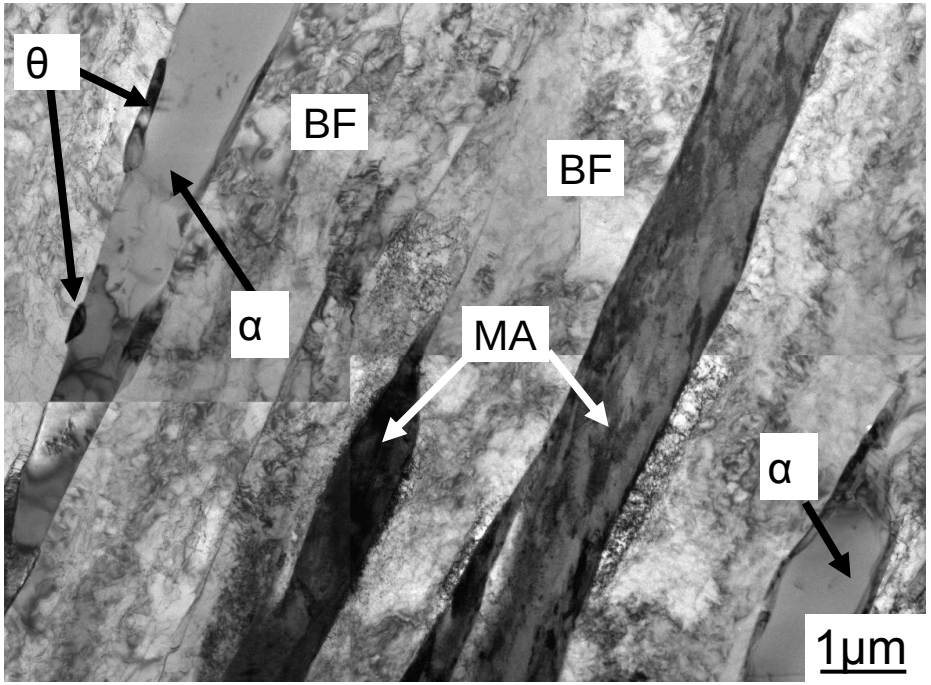


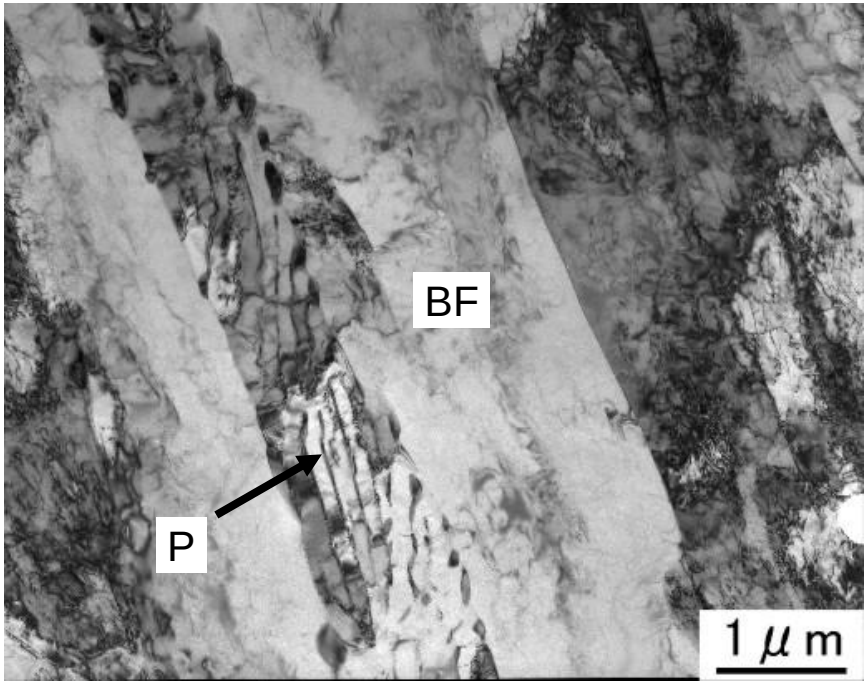
BF : Bainitic Ferrite P :Pearlite

α : Ferrite θ: Cementite

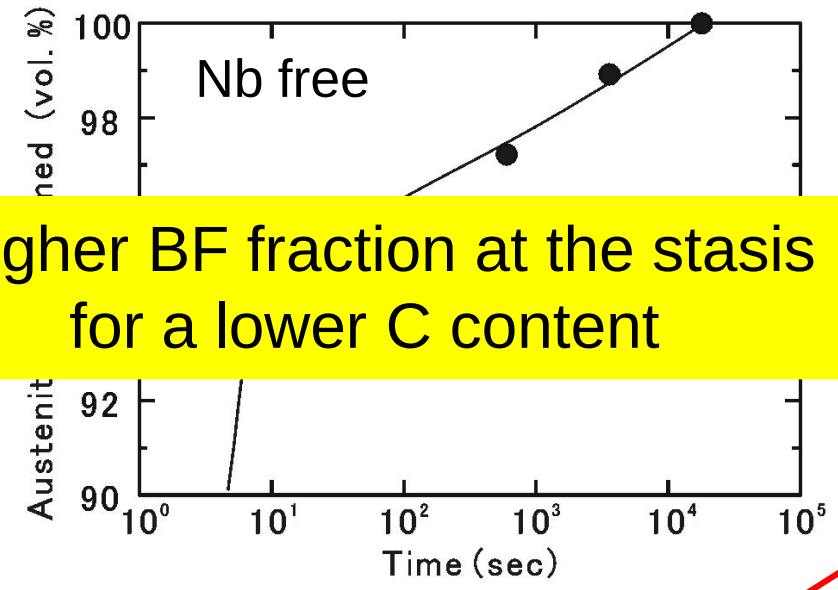
MA :Martensite-Austenite constituent

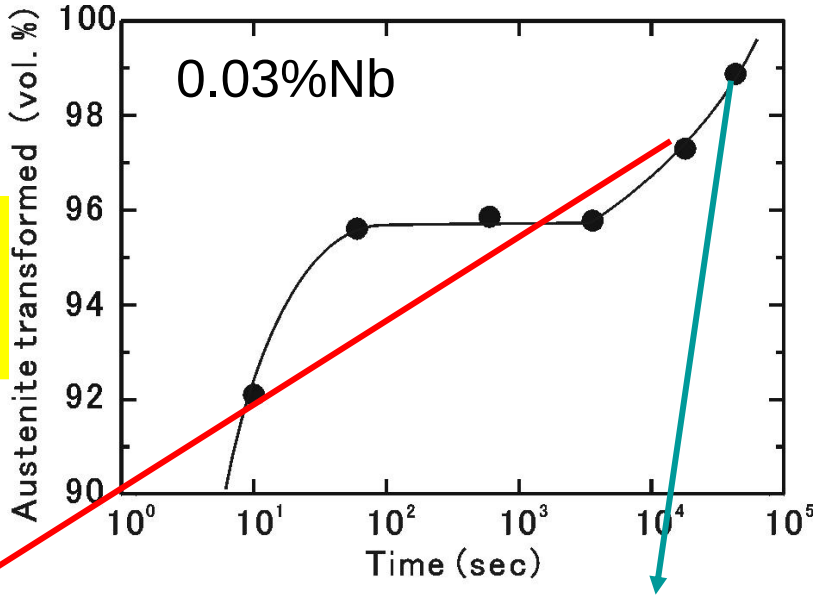
Dislocation-free ferrites of new orientations containing θ forms after the stasis.



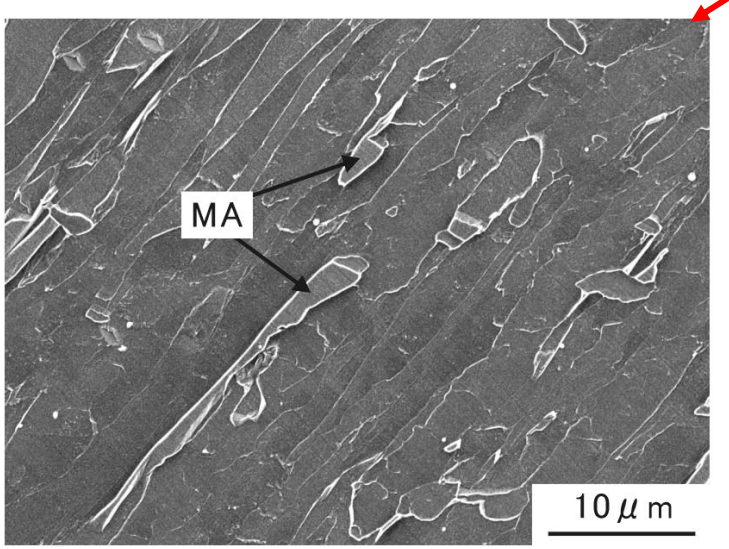


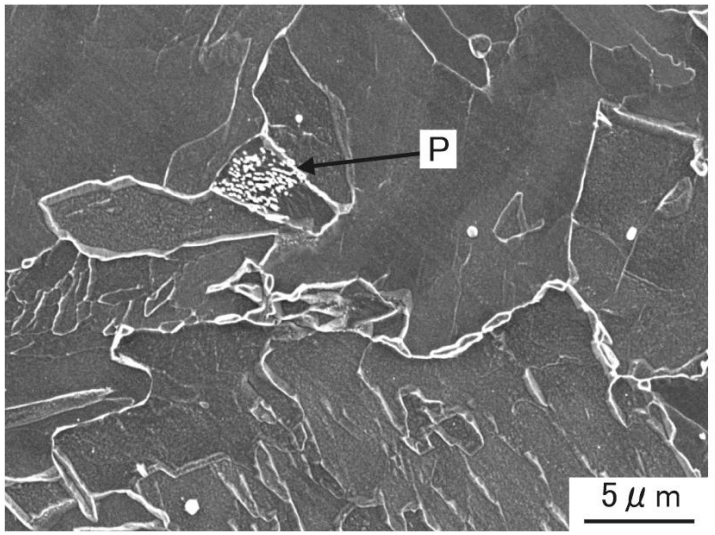
Fe-0.05C-1.5Mn alloys, transformed at 853K





A higher BF fraction at the stasis for a lower C content

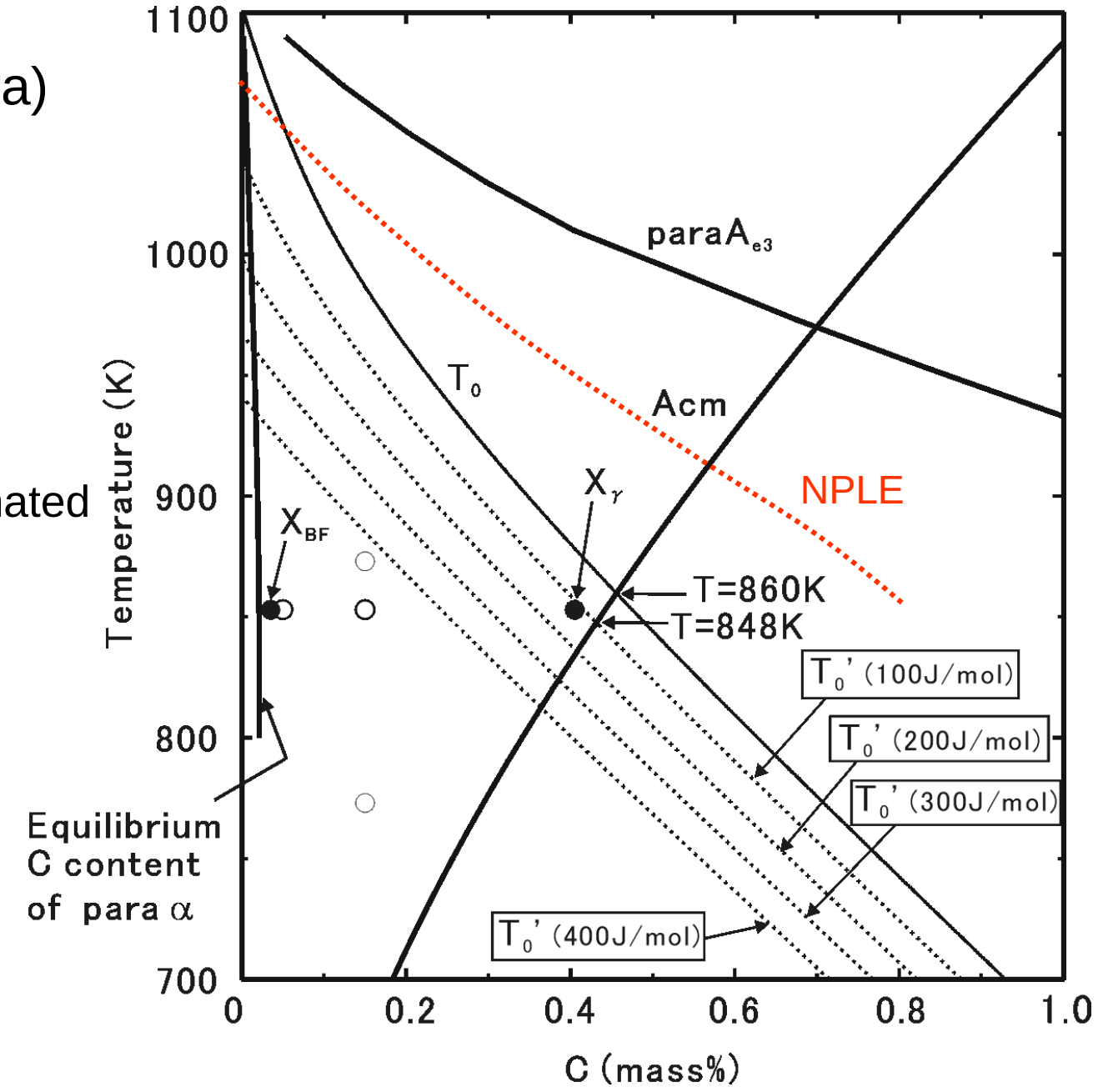




Fe-1.5Mn-C (para) phase diagram

○: Initial C content

●: C contents estimated at the stasis by a lever rule

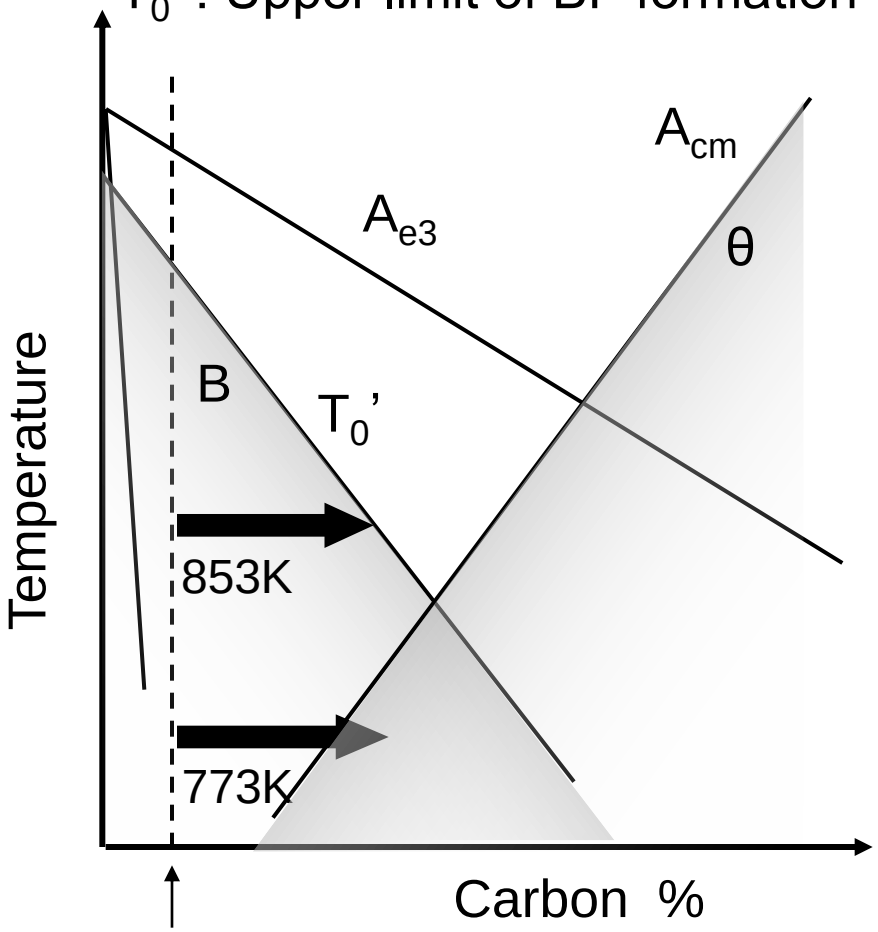


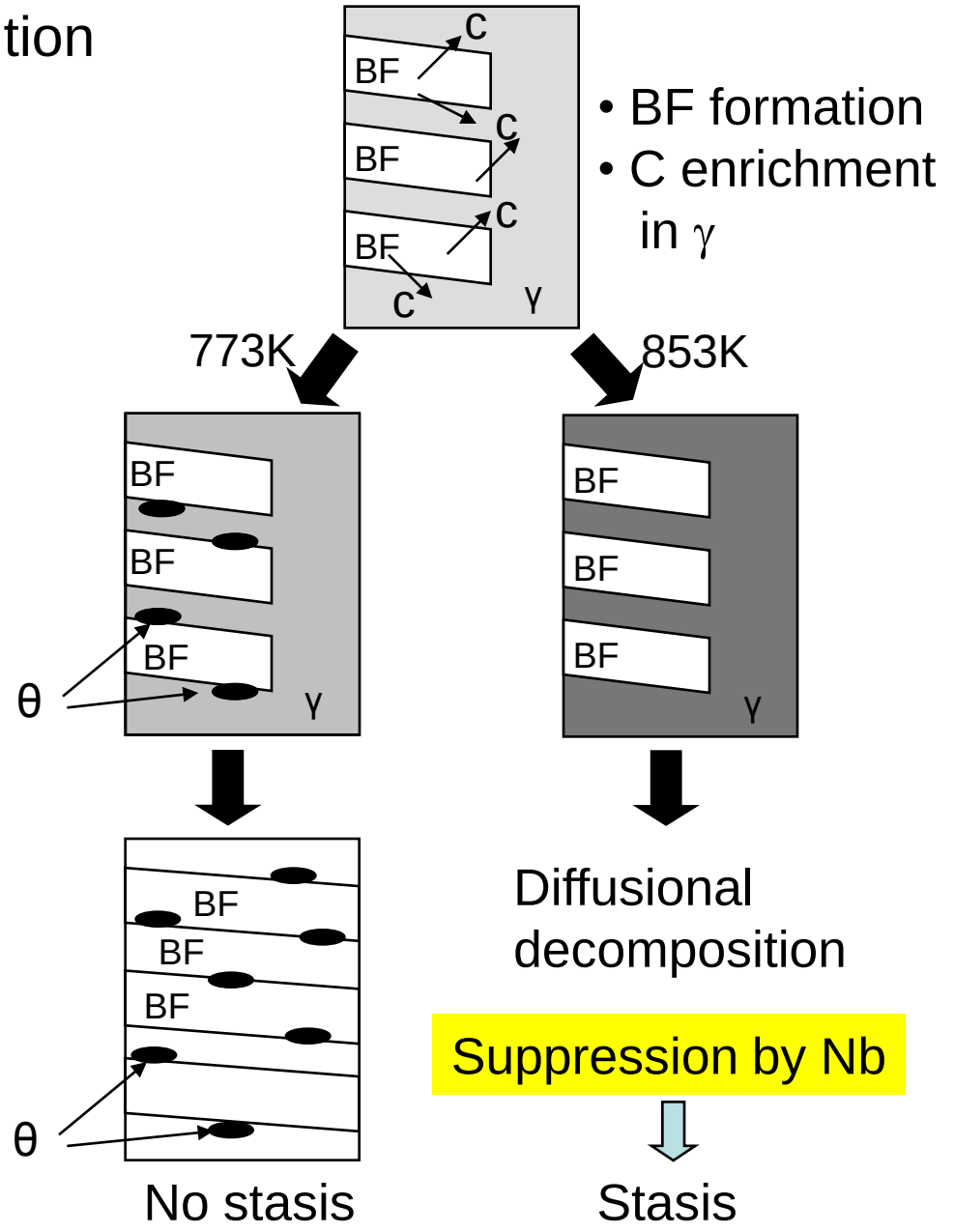
Mechanism for transformation stasis with Nb addition

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)

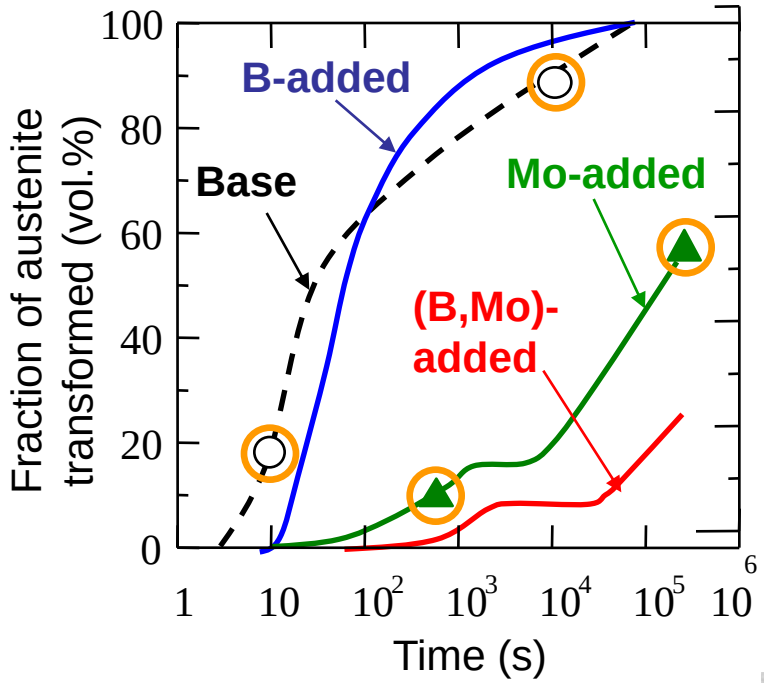
Decrease in diffusion coefficient of carbon

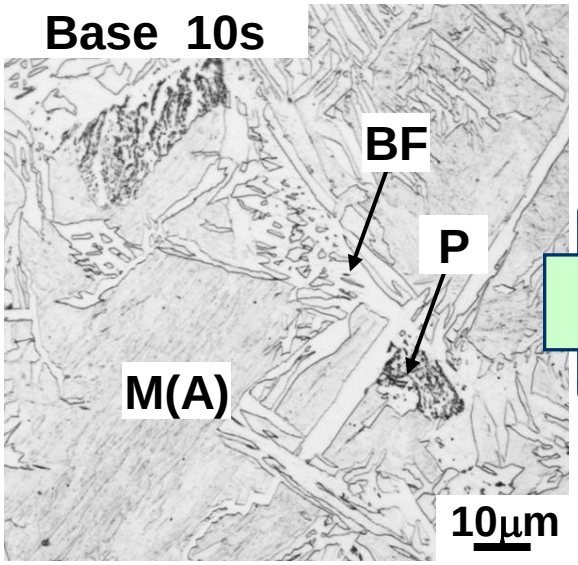
(S. Nanba, H. Morimoto, G. Anami, T. Towada:
Kobe steel Eng. Rep., 47 (1997), 8)

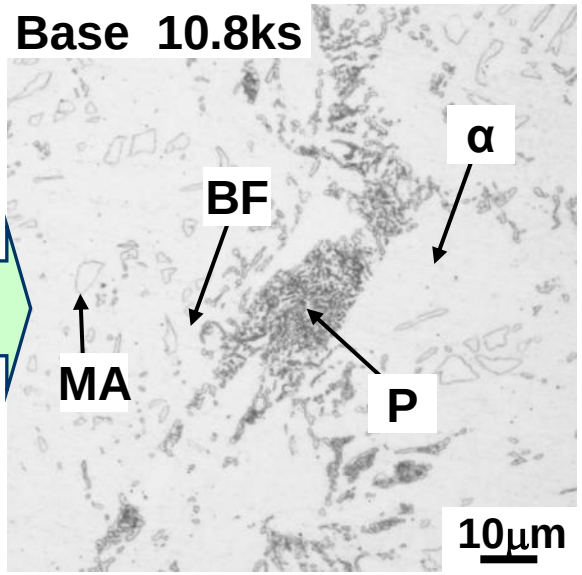
Pinning by Nb(C,N) precipitation

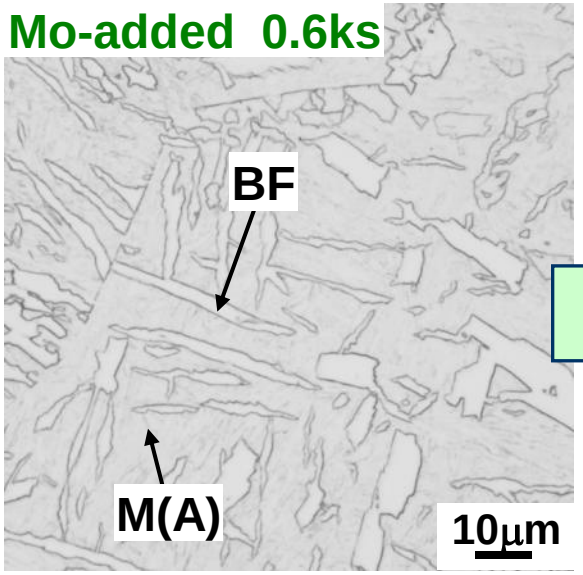
Effect of (B, Mo) addition

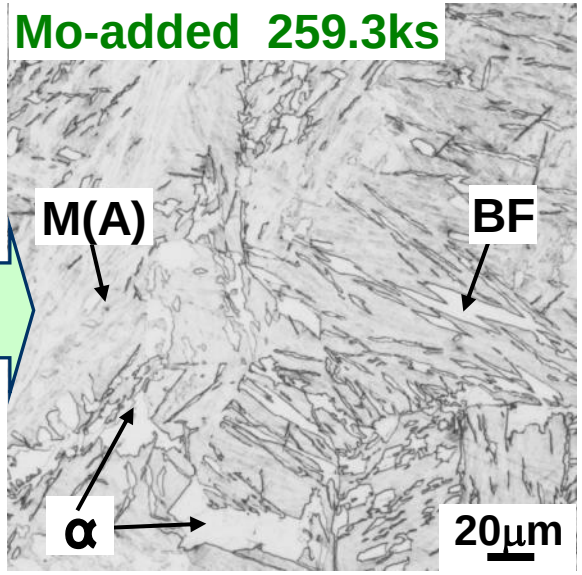
Isothermal transformation at 873K (OM)











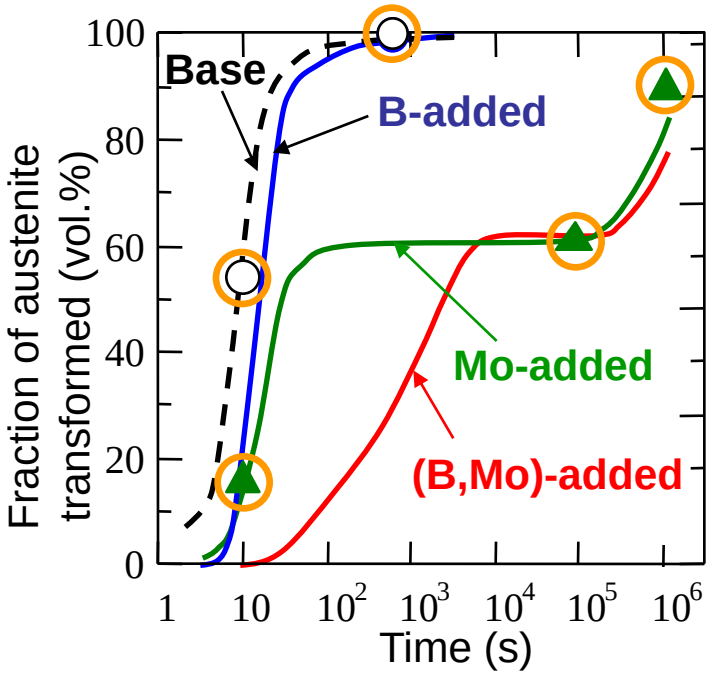
Addition of Mo

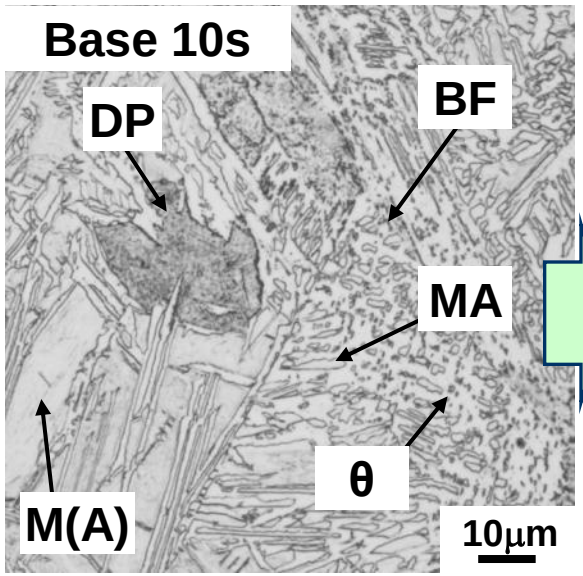
Suppression of diffusional transformation

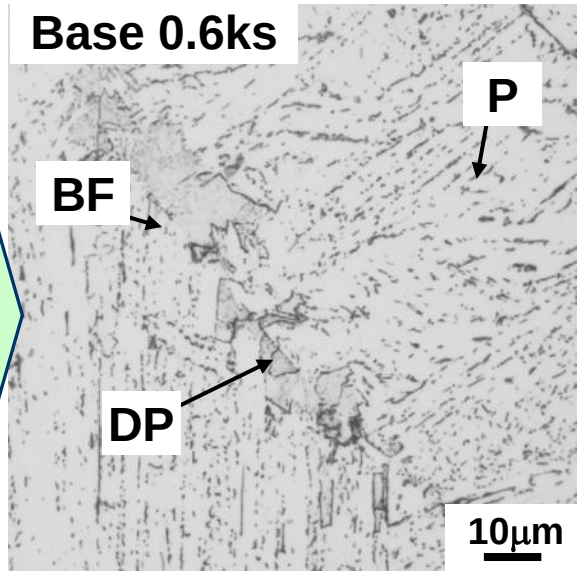
Negligible amount of carbide after the stasis

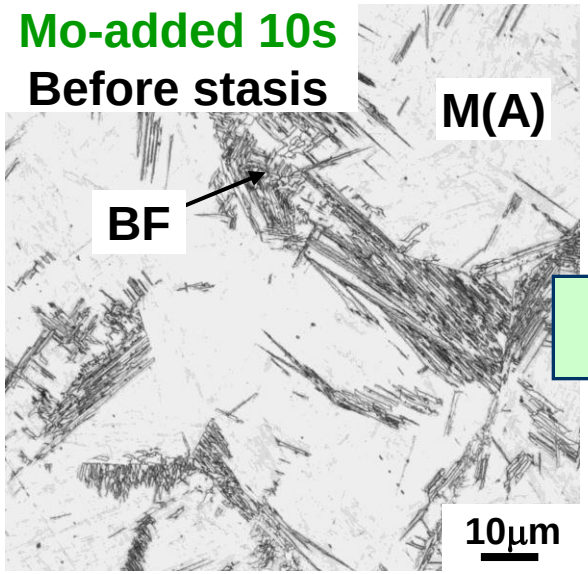
BF: Bainitic Ferrite, α: Ferrite MA: Martensite-Austenite constituent
P: Pearlite M(A): Mertensite(untransformed austenite)

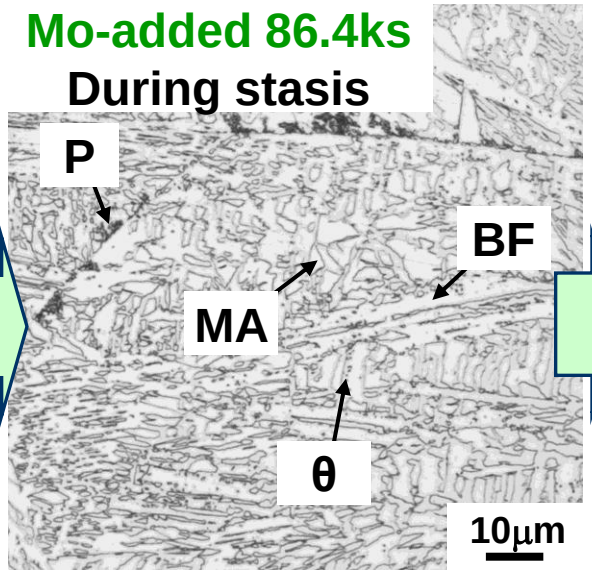
Isothermal transformation at 823K (OM)

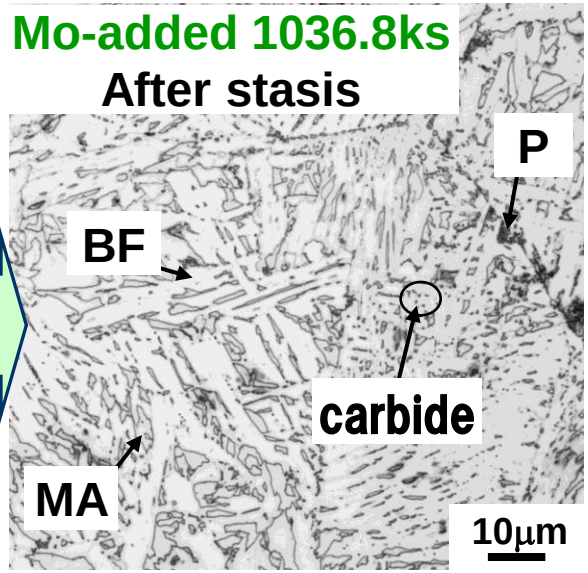










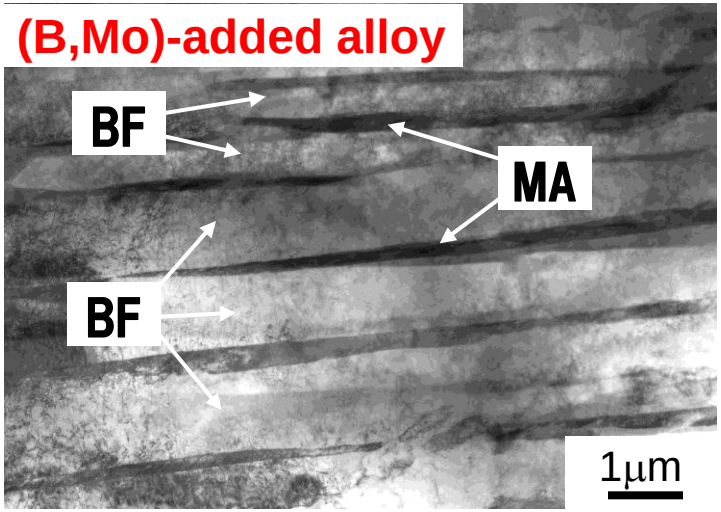


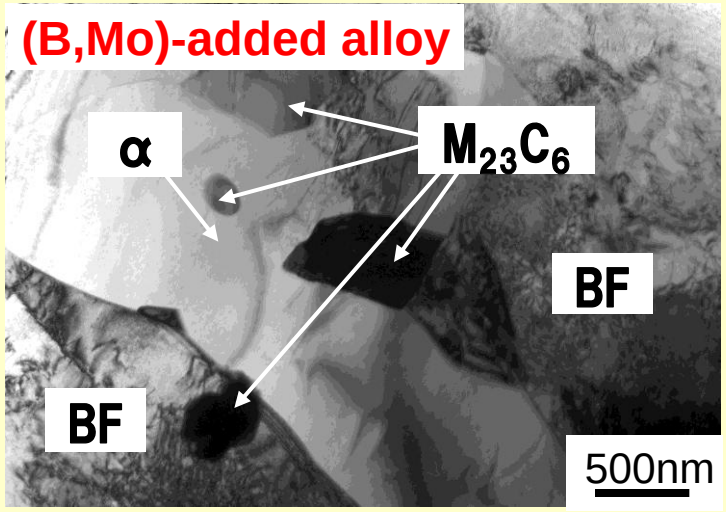
BF: Bainitic Ferrite θ: Cementite Martensite-Austenite constituent

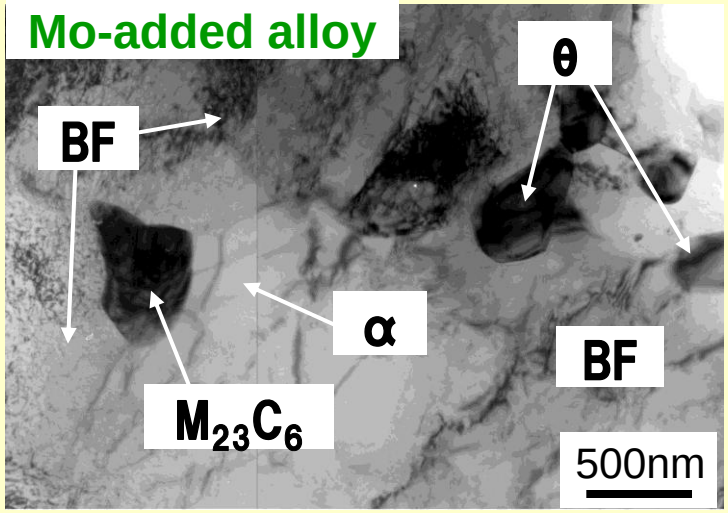
M(A): Martensite (untransformed austenite) P: Pearlite DP: Degenerate Pearlite

TEM microstructure transformed at 823K

10.8 ks (during staisis) → **1036.8 ks (after stasis)**







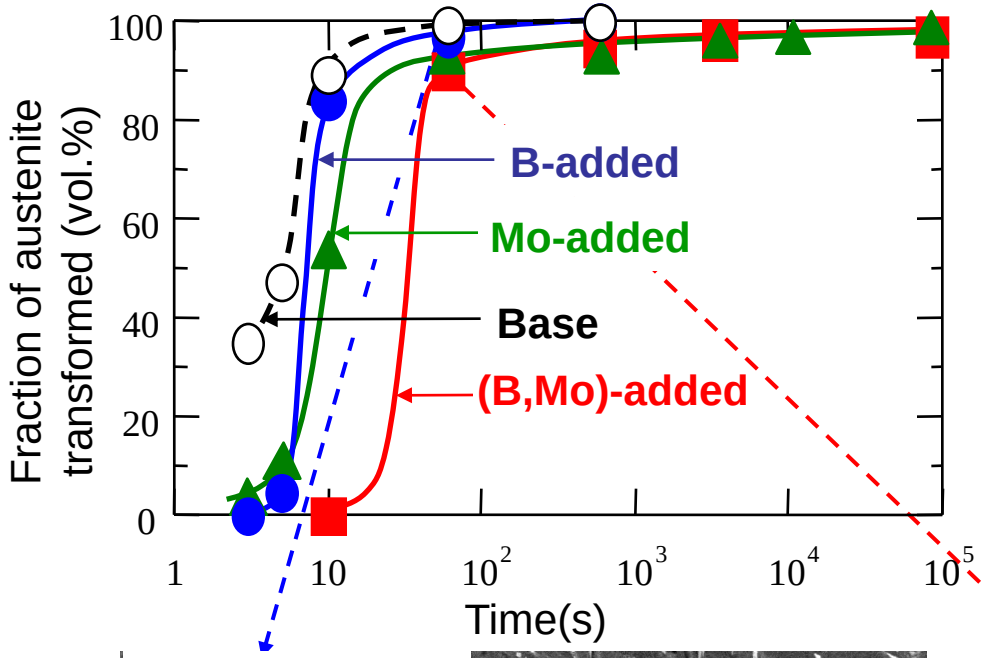
untransformed austenite

During the stasis
→ remainig as interlath **MA**

After the stasis
→ decomposing to **ferrite+carbide**
<diffusional transformation>

BF: Bainitic Ferrite MA: Martensite-Austenite constituent α: Ferrite θ: Cementite $M_{23}C_6$ carbide

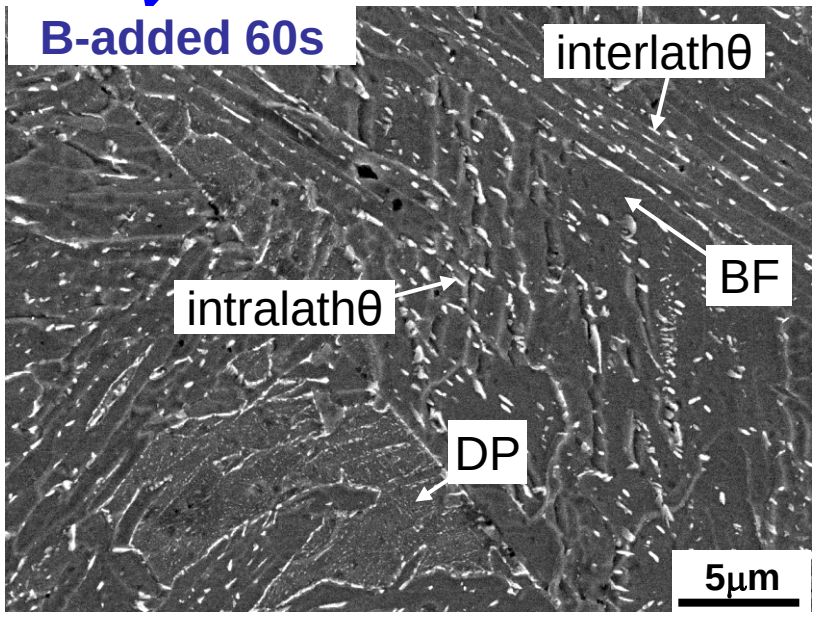
Isothermal transformation at 773K (SEM)

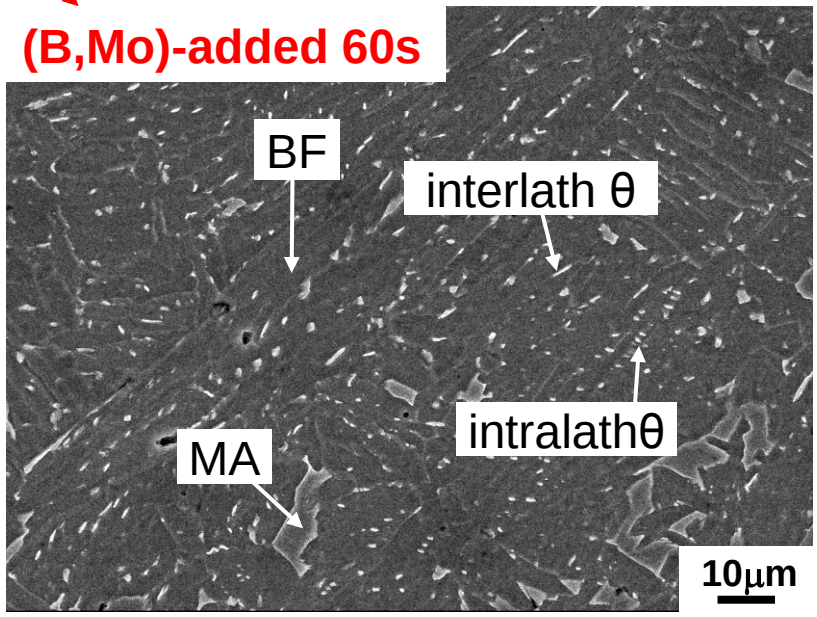


Fast transformation kinetics without much difference

Bainite transformation with θ precipitation

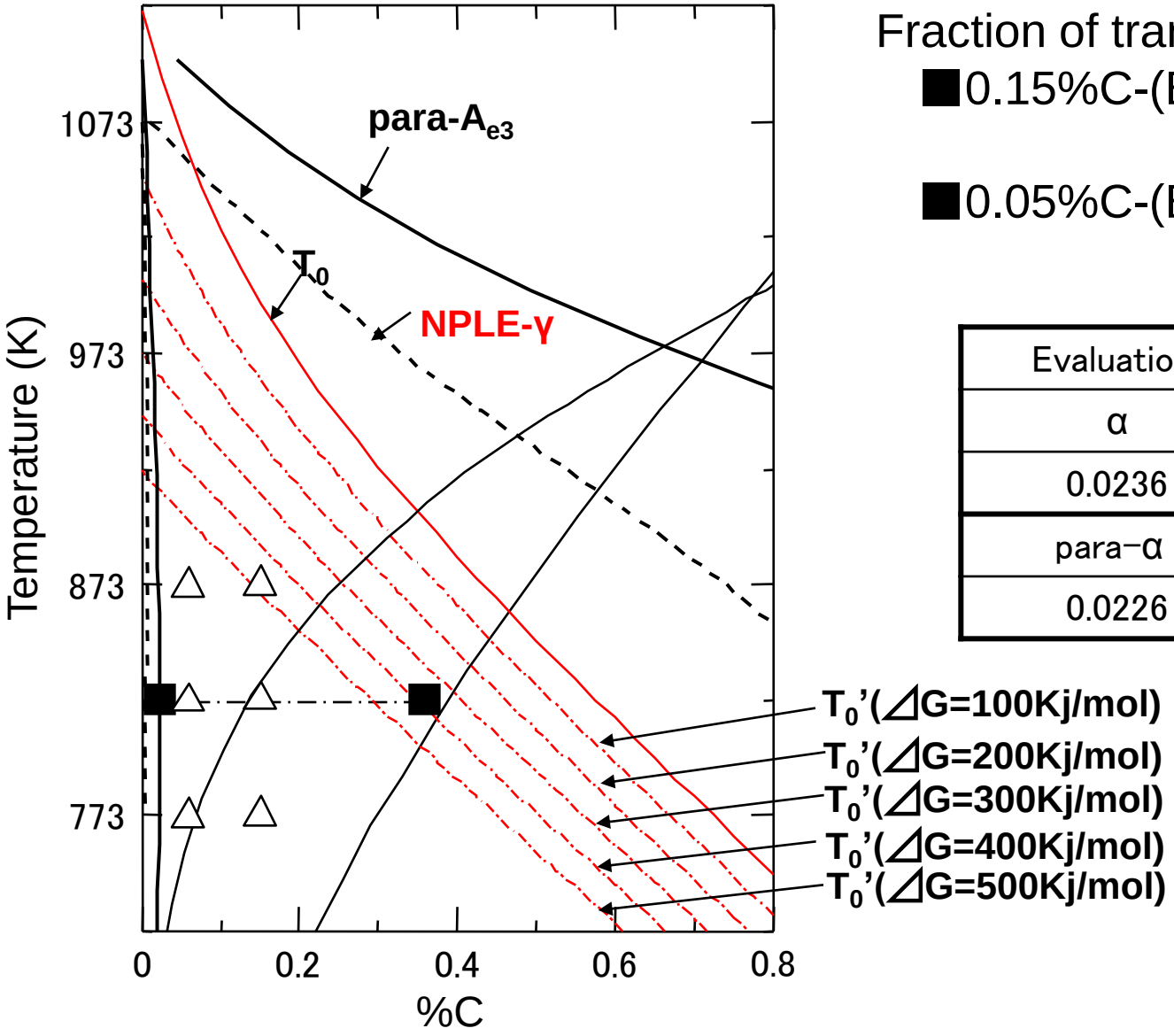
No transformation stasis





BF: Bainitic Ferrite MA: Martensite-Austenite constituent θ: Cementite DP: Degenerate Pearlite

Fe-C-1.5mass%Mn (para)

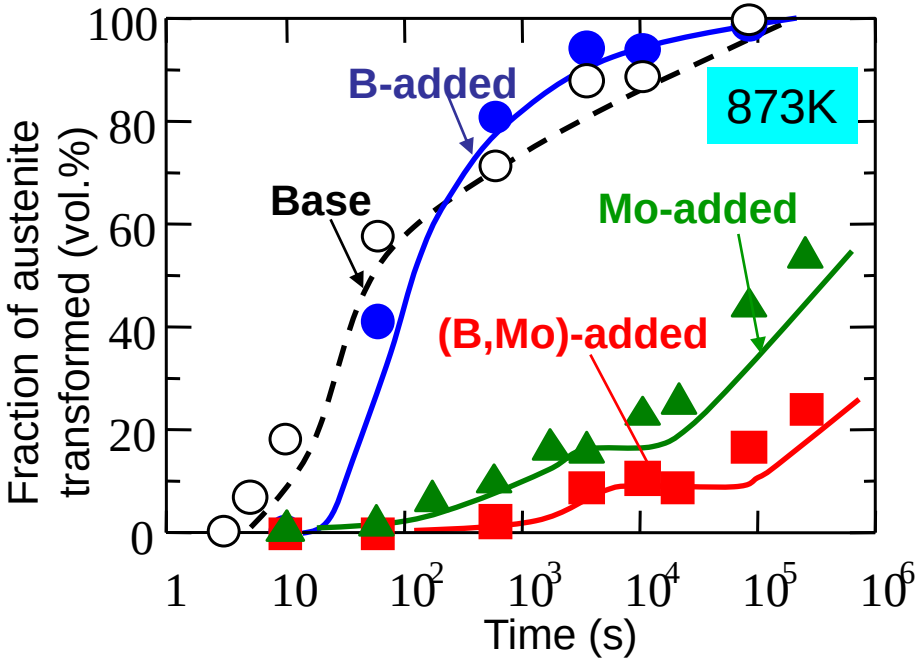


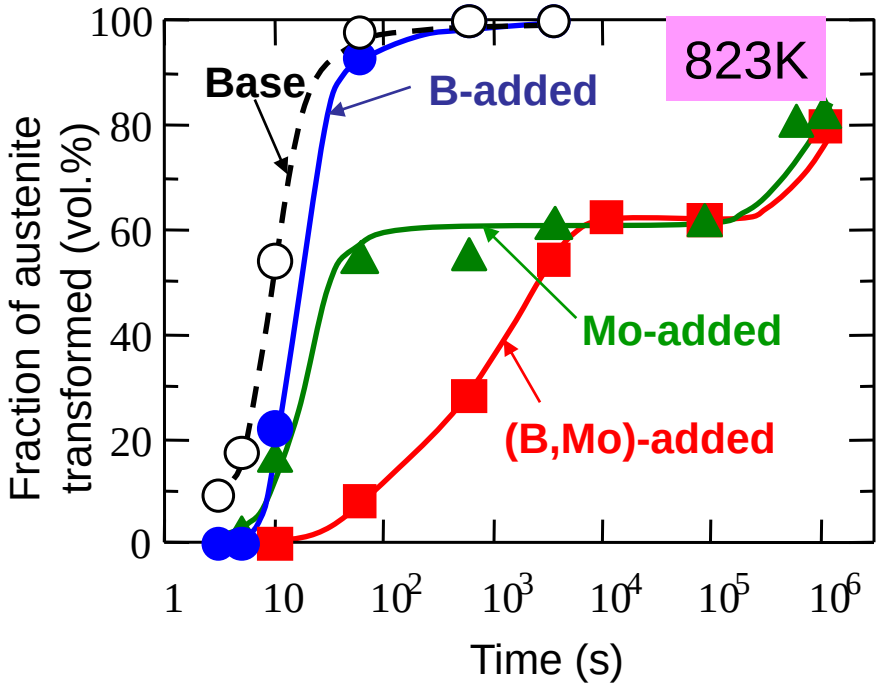
Fraction of transformation at 823K

■0.15%C-(B,Mo)-added alloy
60%

■0.05%C-(B,Mo)-added alloy
92%

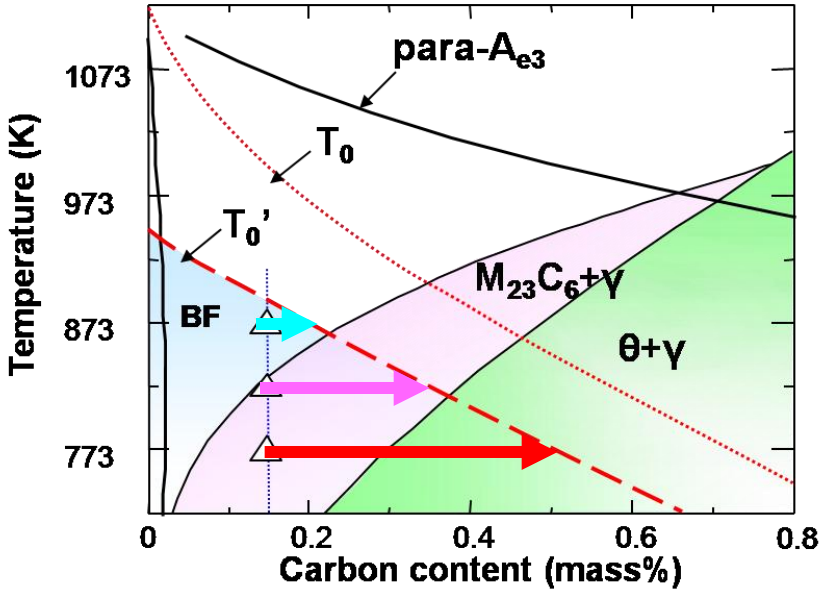
Evaluation %C from the lever rule	
α	γ
0.0236	0.358
para−α	T_0‘ content
0.0226	0.348





Incomplete transformation by Mo addition

Fe-0.15C-1.5Mn(-100ppmB-0.5Mo)



873K, 823K : Carbide-free BF formation
→ Stasis

Restart by α formation at 873K
by $M_{23}C_6$ precipitation at 823K

773K : Bainite transformation
with cementite (no stasis)

(Summary)

1. A transformation stasis in upper bainite transformation appears in Mn-containing low-alloy low-carbon steels microalloyed with Nb and Mo.

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

3. Mo or Nb in solution suppress the nucleation of ferrite at BF/γ interphase boundary in a temperature range where the incomplete transformation of bainite occurs.