Influence of magnetic field on ferrite transformation in an Fe-C-Mn alloy

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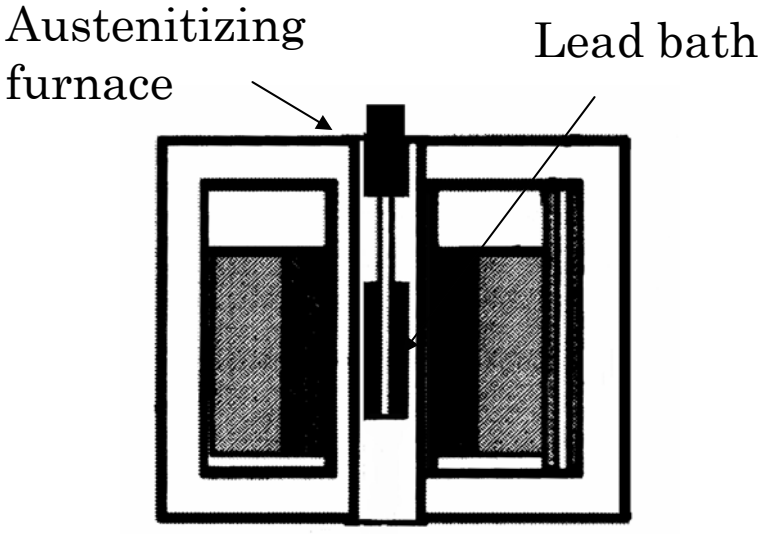
Background

- Heat treatment under magnetic field may provide a new technology of design and control of microstructure of steel.
- A magnetic field accelerates ferrite transformation not only below, but also above the Curie temperature
  M.Enomoto, H. Guo, Y. Tazuke, Y.R. Abe and M. Shimotomai, Metall.Mater. Trans.A, 32A, 2001, p.445.
- In a Fe-0.3C-3Mo alloy transformation stasis occurred and the TTT-diagram bay was raised 30~40°C in a magnetic field of 12 Tesla.
  M.Enomoto, K.M.Wu and M.Kagayama, ALEMI 6th Workshop, 2007, Hamilton*
- In this study we are interested in how a magnetic field influences the growth of ferrite with reference to the fast and slow growth modes and the transition between them.

Experimental procedure

Composition of alloy in wt%	
C	0.10
Mn	2.94
Si	0.019
P	0.002
S	0.0013
Al	< 0.001
N	9 ppm
O	10 ppm

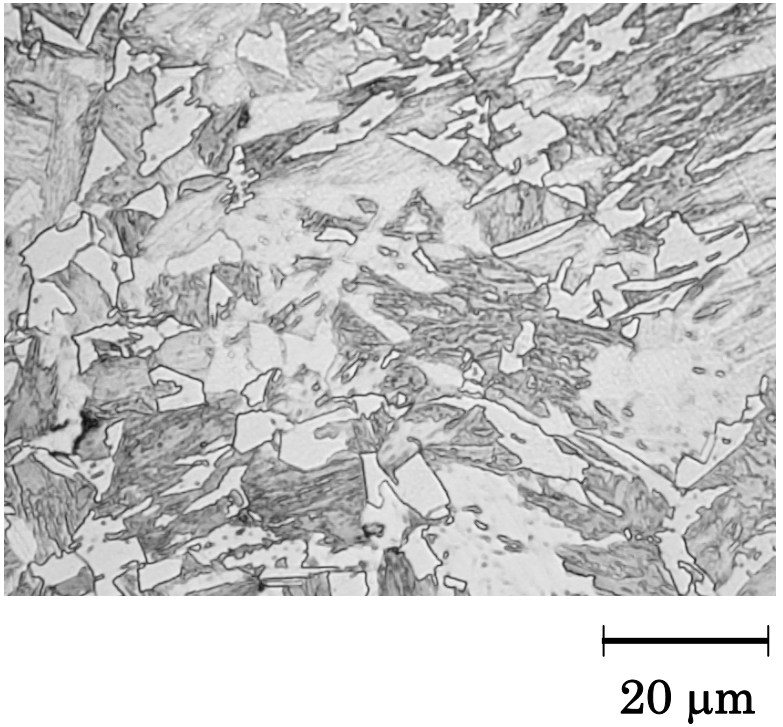


Austenitized at *850 ℃* and isothermally reacted at *550~670 ℃ for 60~1800 s with H=0 (off) and H= 8 Tesla.*

The austenite grain size was d_γ=14 μm

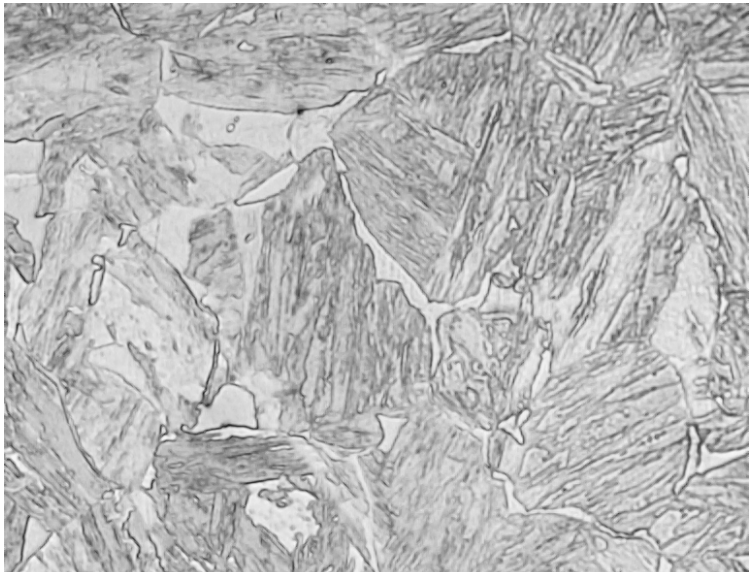
Optical microstructure 590°C 1min

H=0 Tesla



H=8 Tesla

Optical microstructure 670°C 10min



20 μm

H=0 Tesla

H=8 Tesla

Influence of magnetic field on α/γ phase boundaries

Gibbs free energy of an iron alloy in magnetic field,

$$G^*(T,H) = G^*(T,0) - \int_0^H MdH$$

Using Magnetization M is calculated phenomenologically from Weiss molecular field theory.

Alloying elements affect the Curie temperature and magnetic moment of iron. Thus, the free energy change in Fe-X alloys can be evaluated assuming that Mn as well as C are dilute.

The demagnetization field is N=0.33 for a spherical particle, and N=0.1~0.2 if magnetization is along the long direction of precipitates.

T_c and m of Fe vary with alloying,

For dilute alloys (x is mole fraction of alloying element) ,

$$T_C = T_C^\circ + \frac{dT_C}{dx}x = T_C^\circ(1+ax)$$

$$m = m_{Fe} + \frac{dm}{dx}x = m_{Fe}(1+bx)$$

$$T_C = \frac{(j+1)Nm^2w}{3jk}$$

Alloying element	dT_C/dx °C/at%	a	dm/dx , μ_B	b
V	7.5	0.72	−2.68	−1.22
Cr	−1.5	−0.14	−2.29	−1.04
Mn	−15	−1.44	−2.11	−0.96
Co	12	1.15	1.11	0.5
Ni	−3.6	−0.34	1.30	0.59
Mo	0.0	0.0	−2.11	−0.96
Si	−3.5	−0.34	−2.29	−1.04

$a = 100(dT_C/dx)/T_C^\circ$, $b = (dm/dx)/m_{Fe}$

No correlation between T_C (or a) and m (or b).

Magnetization in dilute Fe-X alloys

$$M = NmB_j(\alpha + \Delta\alpha) = Nm_{Fe}(1+bx)\{B_j(\alpha) + B_j'(\alpha)\Delta\alpha\}$$

$$G^H \equiv -\int_0^H MdH = (1-x)\mu_{Fe}{}^H + x\mu_X{}^H$$

To retain the terms of the 1st order of x, the chemical potential is given by,

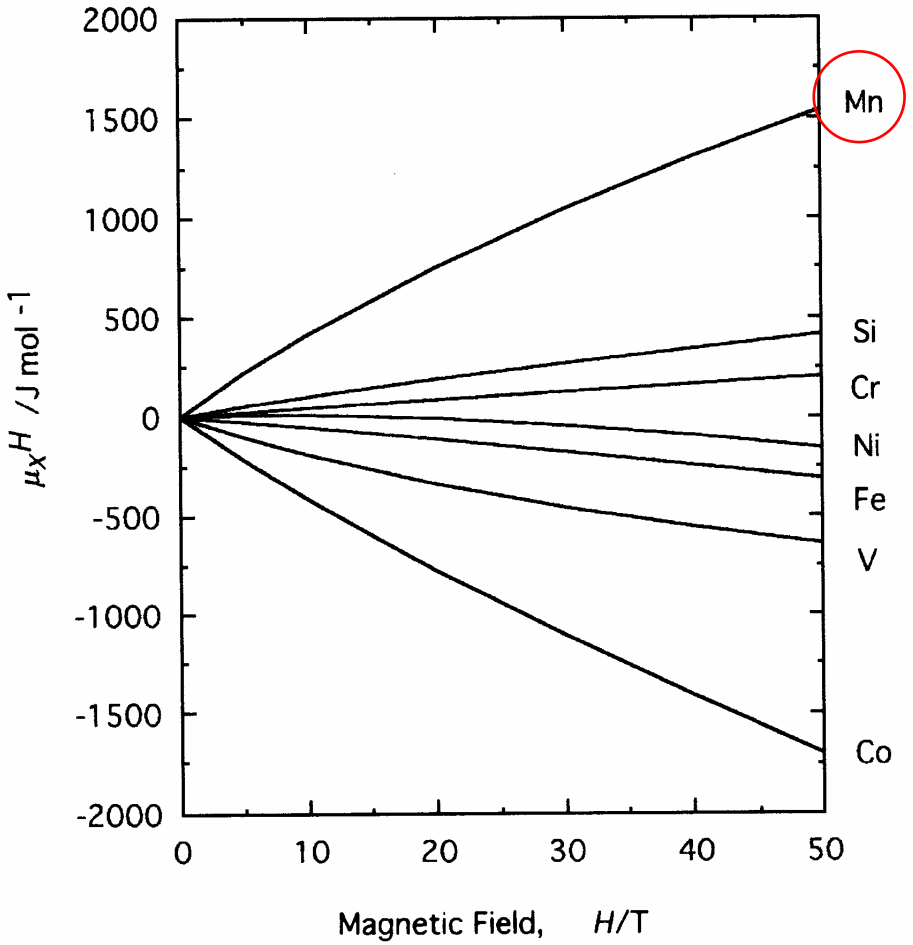
$$\mu_{Fe}^H = -Nm_{Fe}\int_0^H B_j(\alpha)dH$$

$$\mu_X^H = -Nm_{Fe}\int_0^H \{(1+b)B_j(\alpha) + A' B_j(\alpha)\}dH$$

where,

$$A = \frac{kTa\alpha + (b-a)m_{Fe}H}{kT - 3kT_C \circ jB_j'(\alpha)/(j+1)}$$

μ_X^H vs. H



Influence on the stability of ferrite phase

If 'X' raises T_C, it will stabilize ferrite in a magnetic field.

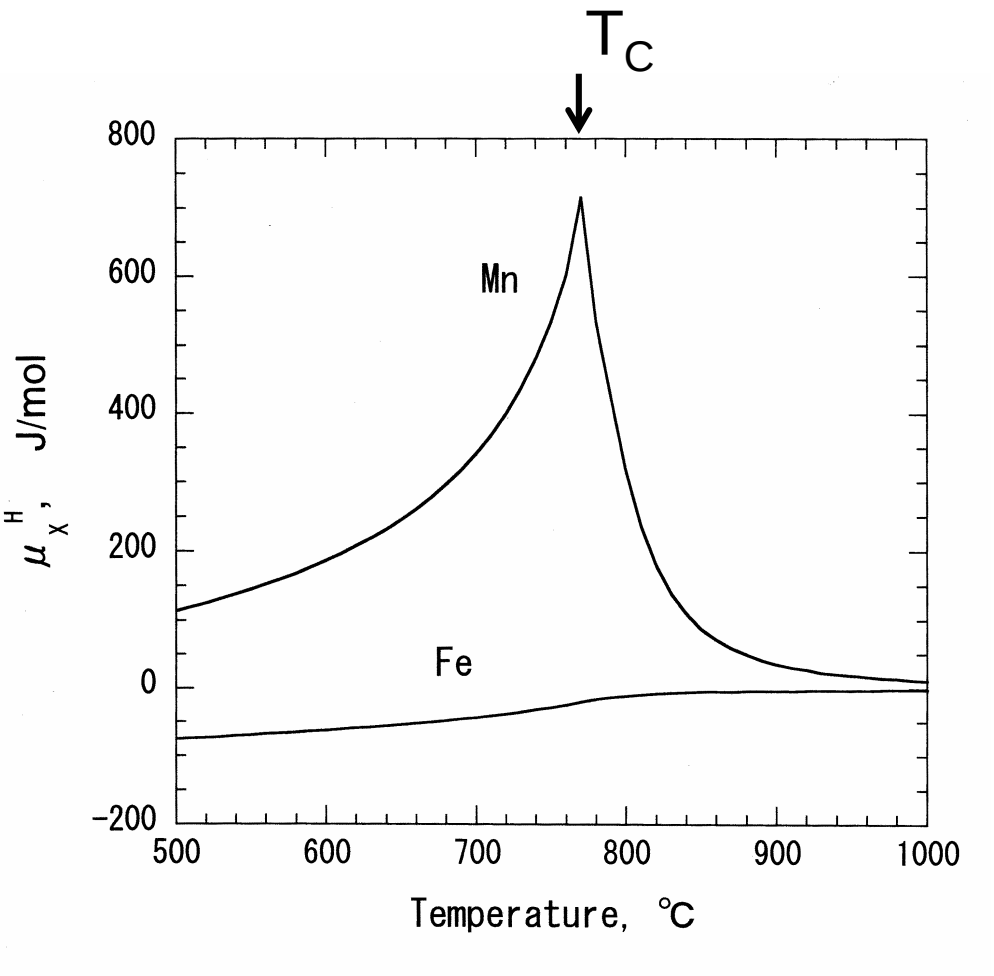
If 'X' increases m, it will also stabilize ferrite.

Mn destabilizes ferrite because it lowers T_C and decreases m.

Ni slightly stabilizes ferrite because it increases m, but lowers T_C.

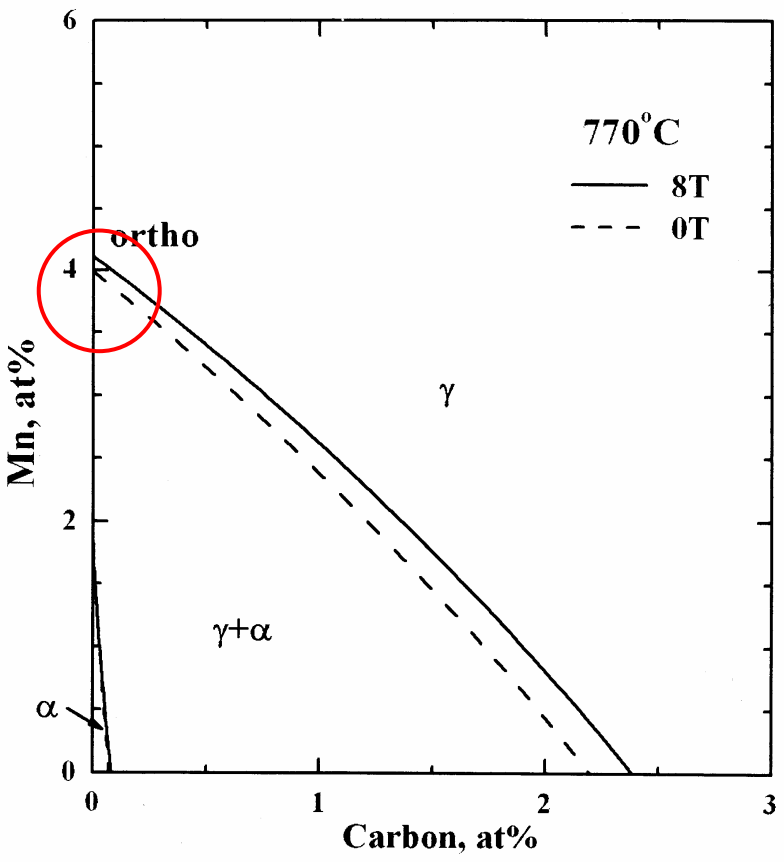
$\mu_{Mn}{}^{H}$ vs. T

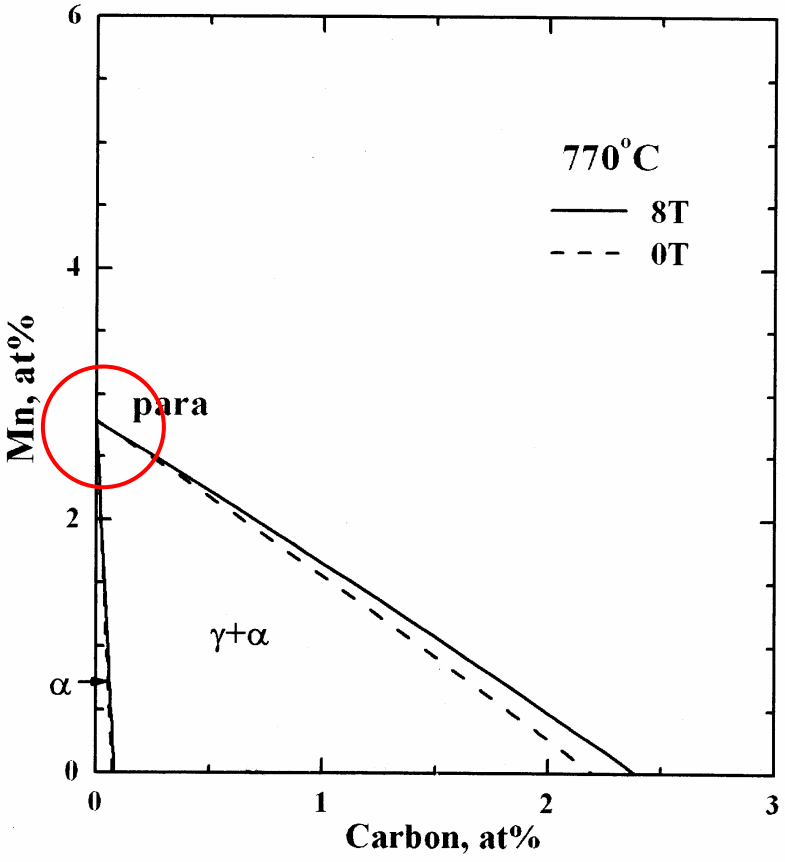
(continued)



The destabilization effect is largest in the vicinity of T_C. However, the effect is not very large because of the low Mn content.

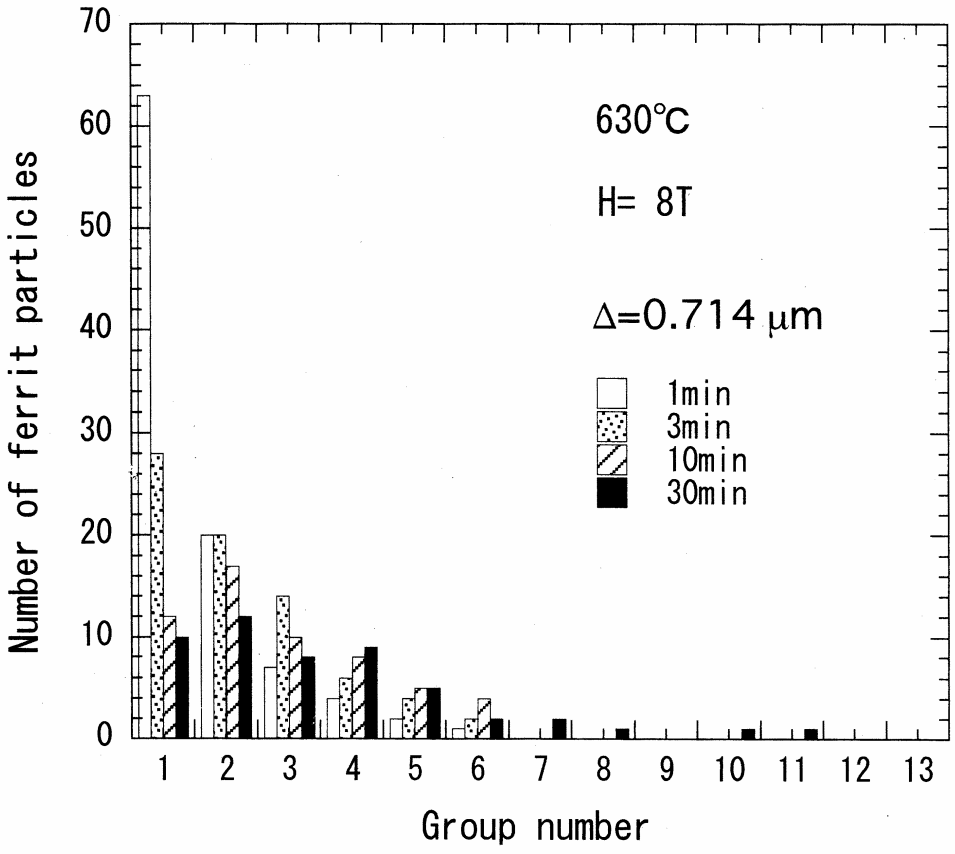
Influence of magnetic field on α/γ boundaries #2





Ferrite particle number *per unit area of grain boundary*

Schwartz-Saltykov analysis



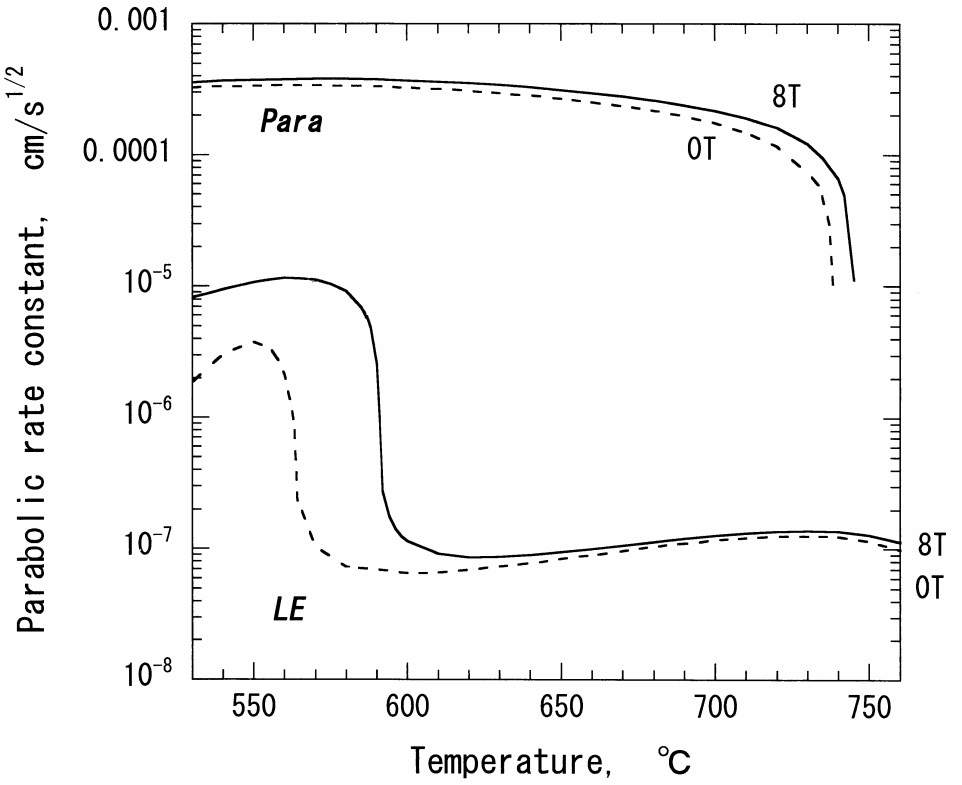
$$N = \frac{1}{\Delta}\sum_{i=1}^{k} \alpha_i n_i$$

Δ; Size of group

α_i; Numerical coefficient to calculate particle number in *three dimensions*

n_i; Number of particles of the i-th size group observed in *two-dimensional section*

Calculated parabolic growth rate constants



Fe-0.10C-3.0Mn alloy

Para ; rate-controlled by carbon diffusion

PLE; rate-controlled by Mn volume diffusion

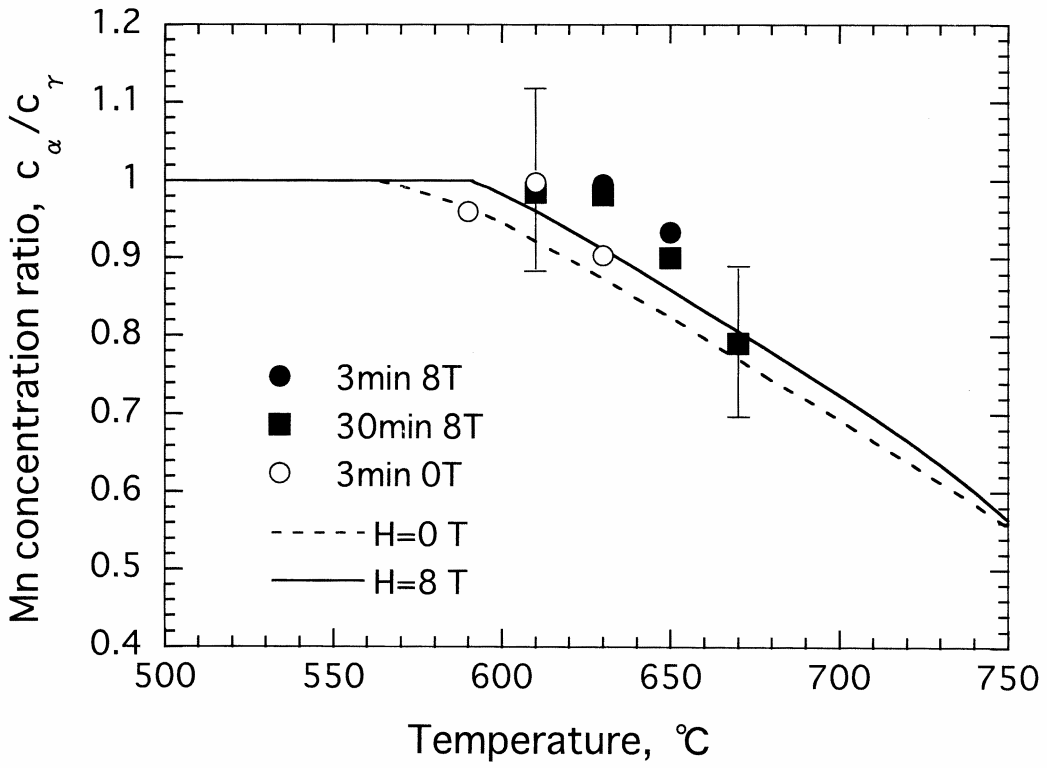
NPLE; rate-controlled by carbon diffusion

The influence of magnetic field is not very large in the Para mode.

PLE/NPLE transition temperature varies considerably by magnetic field. So does the parabolic rate constant in NPLE mode.

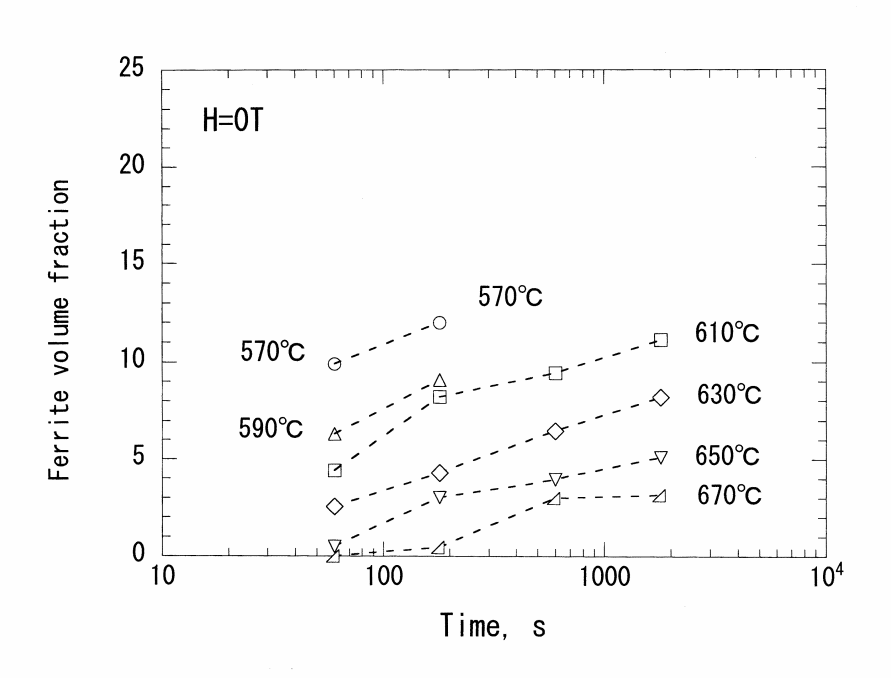
Mn partition between ferrite and austenite matrix

SEM-EDX



In calculation Mn partition starts to occur at 30~40°C higher temperatures in magnetic fields.

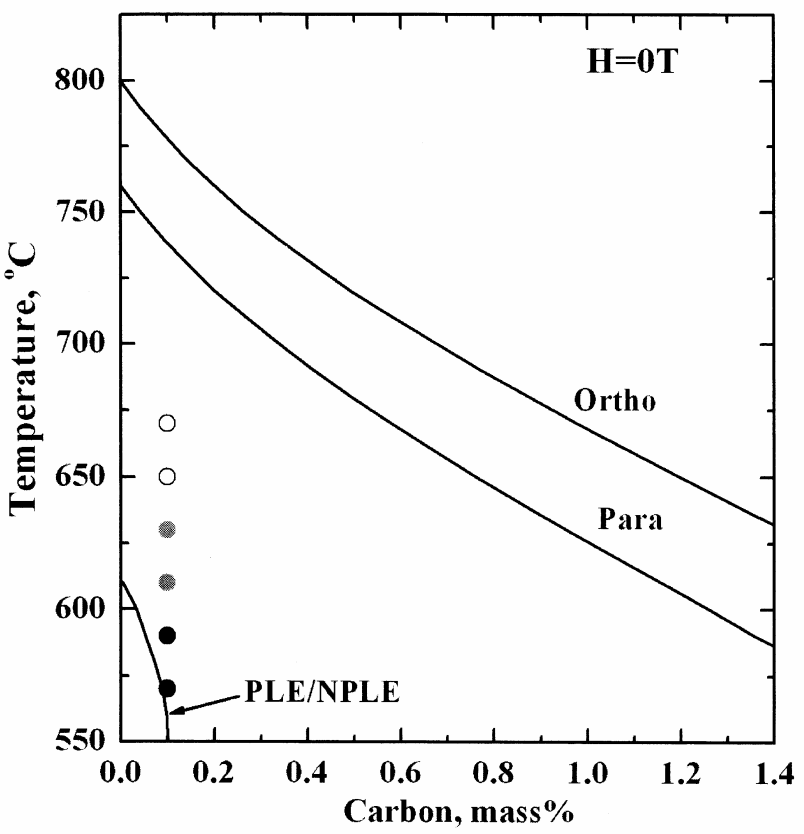
Ferrite volume fraction

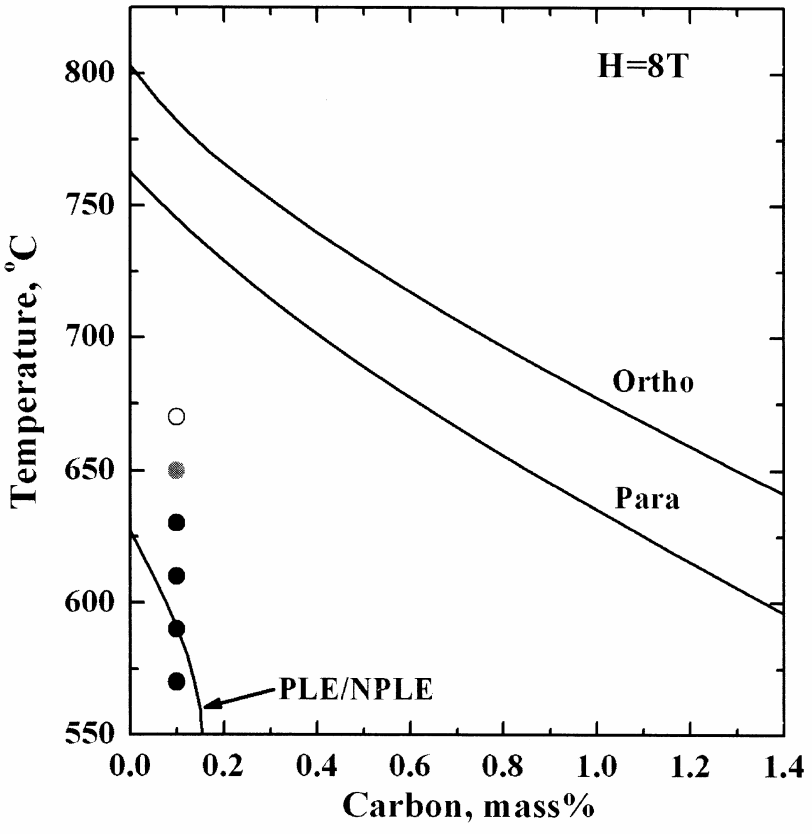


The volume fraction is increased by magnetic field. The amount of increase appears to be greater at lower temperatures.

It seems that the transition from slow growth to fast growth occurs gradually or over a temperature range.

Transition between slow and fast growth





The transition appears from the slow to the fast growth was observed to occur in the PLE region. But it was rather gradual, probably because the austenitizing temperature was low.

Summary

The influence of *an external magnetic field of 8 Tesla* on ferrite transformation was studied in an Fe-0.10 mass% C-2.94mass% Mn alloy.

- The transformation kinetics were accelerated considerably in the magnetic field at lower temperatures, where Mn partition does not occur.
- At higher temperatures where Mn is partitioned between ferrite and austenite matrix the transformation is accelerated to a lesser extent.
- This may be attributed to the slow growth controlled by Mn diffusion.
- It is possible that Mn destabilizes ferrite phase and partially offset the accelerating effect of transformation in a magnetic field, if Mn concentration is large (~3% or more).