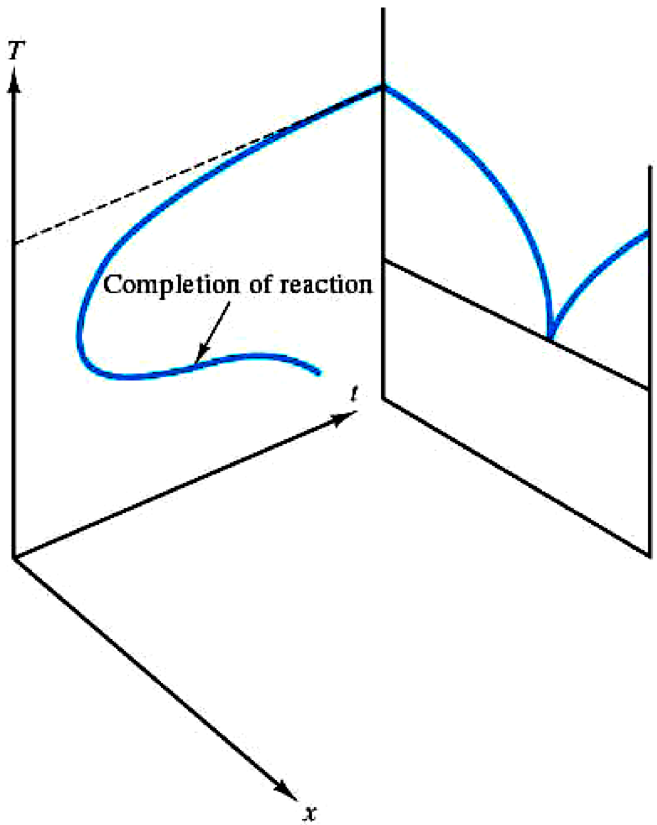
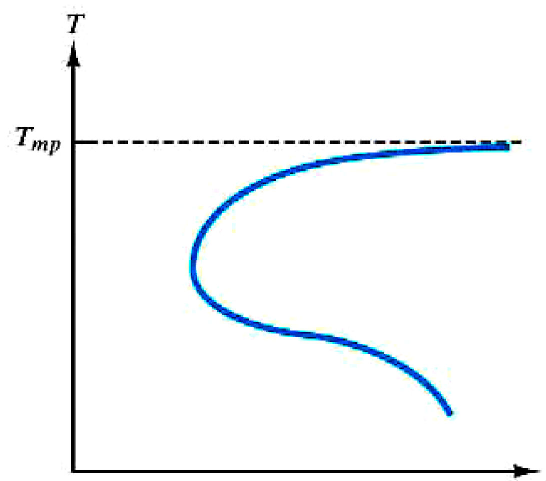
10. Phase Transformation

- phase transformation
  thermodynamics, nucleation
  interface, growth
- T-T-T curve
- martenstic transformation
- tempering

Fundamental Concepts

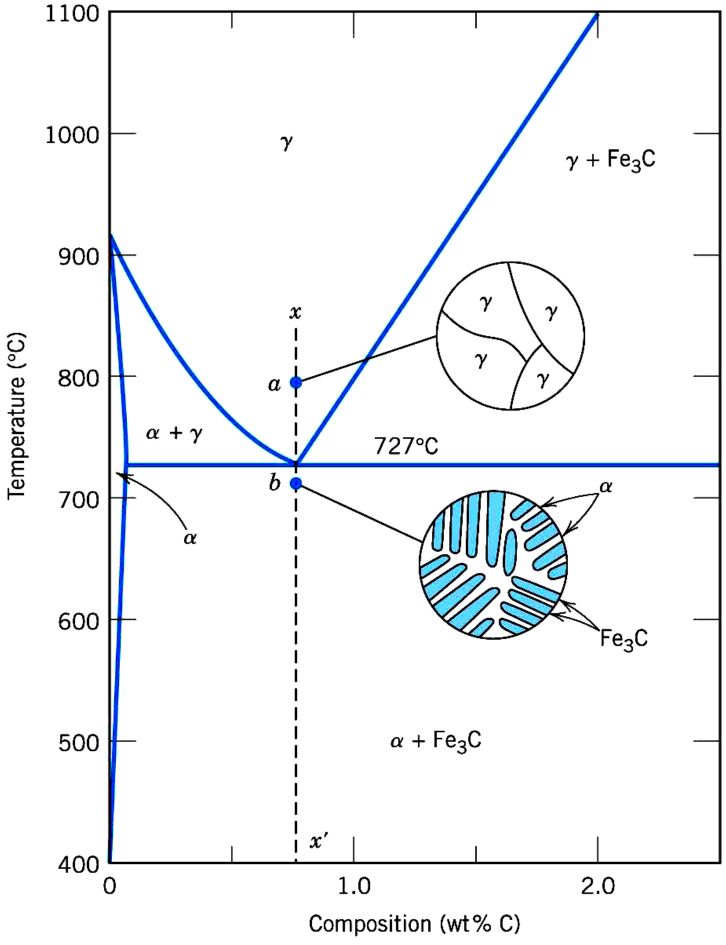
- ❑ phase diagram ← thermodynamic equilibrium
- ❑ real system ← non-equilibrium
- ❑ time → kinetics
- ❑ phase transformation





Fundamental Concepts

- isothermal transformation- temperature-microstructure



just below
eutectoid T

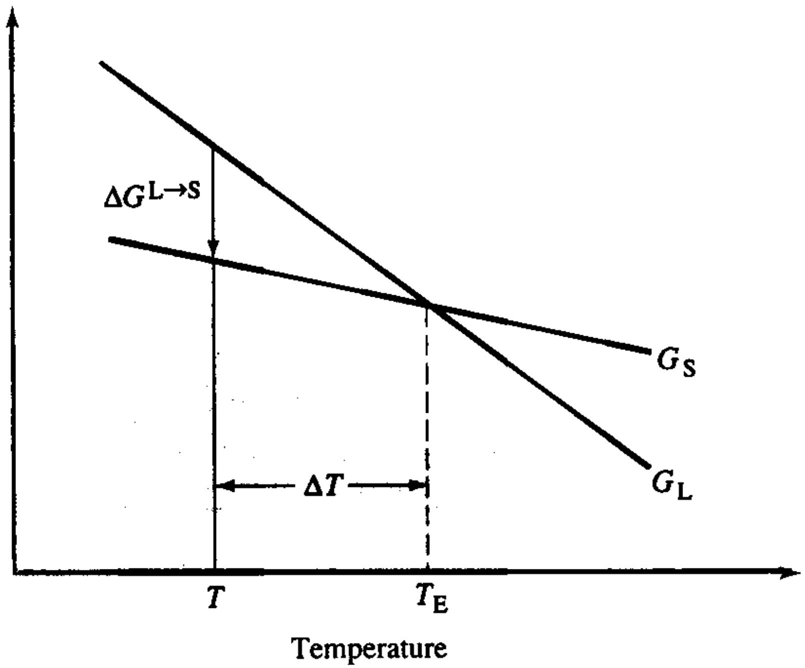
coarse
pearlite

well below
eutectoid T

fine
pearlite

Phase Transformation

- driving force: free energy change



$$\Delta G^{L\to S} = \Delta H^{L\to S} - T\Delta S^{L\to S}$$

$$(\Delta G^{L\to S} = G_S - G_L)$$

$$at\ T = T_E,\ \Delta G^{L\to S} = 0$$

$$\Delta S^{L\to S} = \frac{\Delta H^{L\to S}}{T_E}$$

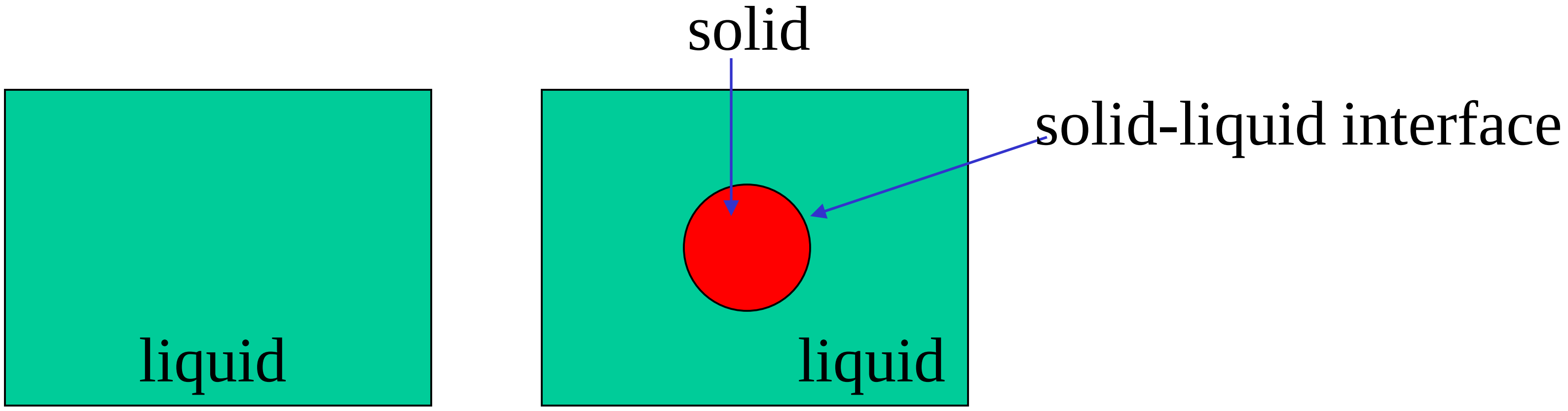
$$\Delta G^{L\to S} = \frac{\Delta H^{L\to S}}{T_E}\Delta T (= T_E - T)$$

For solidification, $\Delta H^{L\to S} < 0$ (exothermic)

$T < T_E,\ \ \Delta T > 0,\ \ \ \Delta G^{L\to S} < 0$ thermodynamically favorable

Phase Transformation

- opposing force: phase boundary

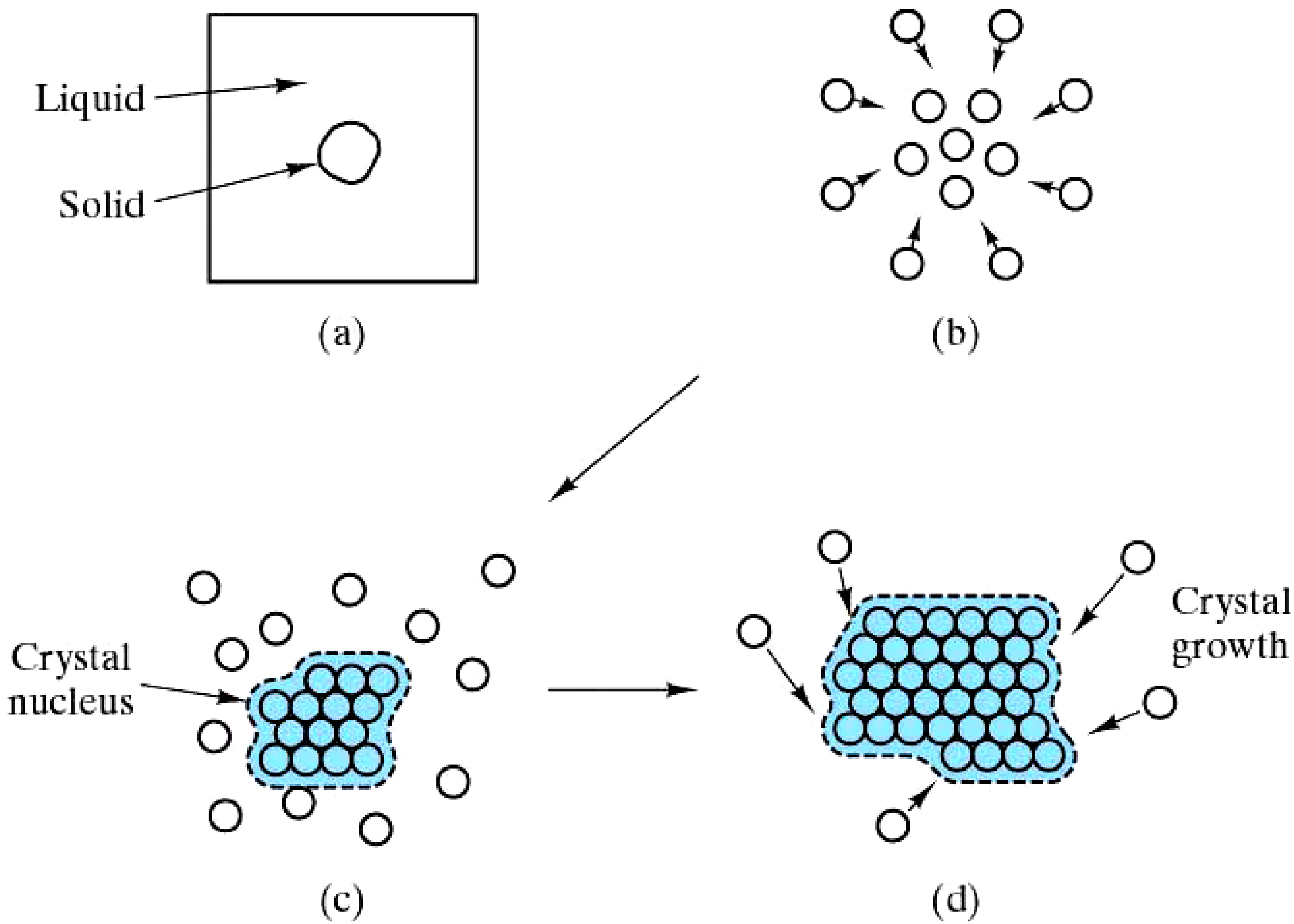


- phase boundary- a few atoms thick- 2-D defect

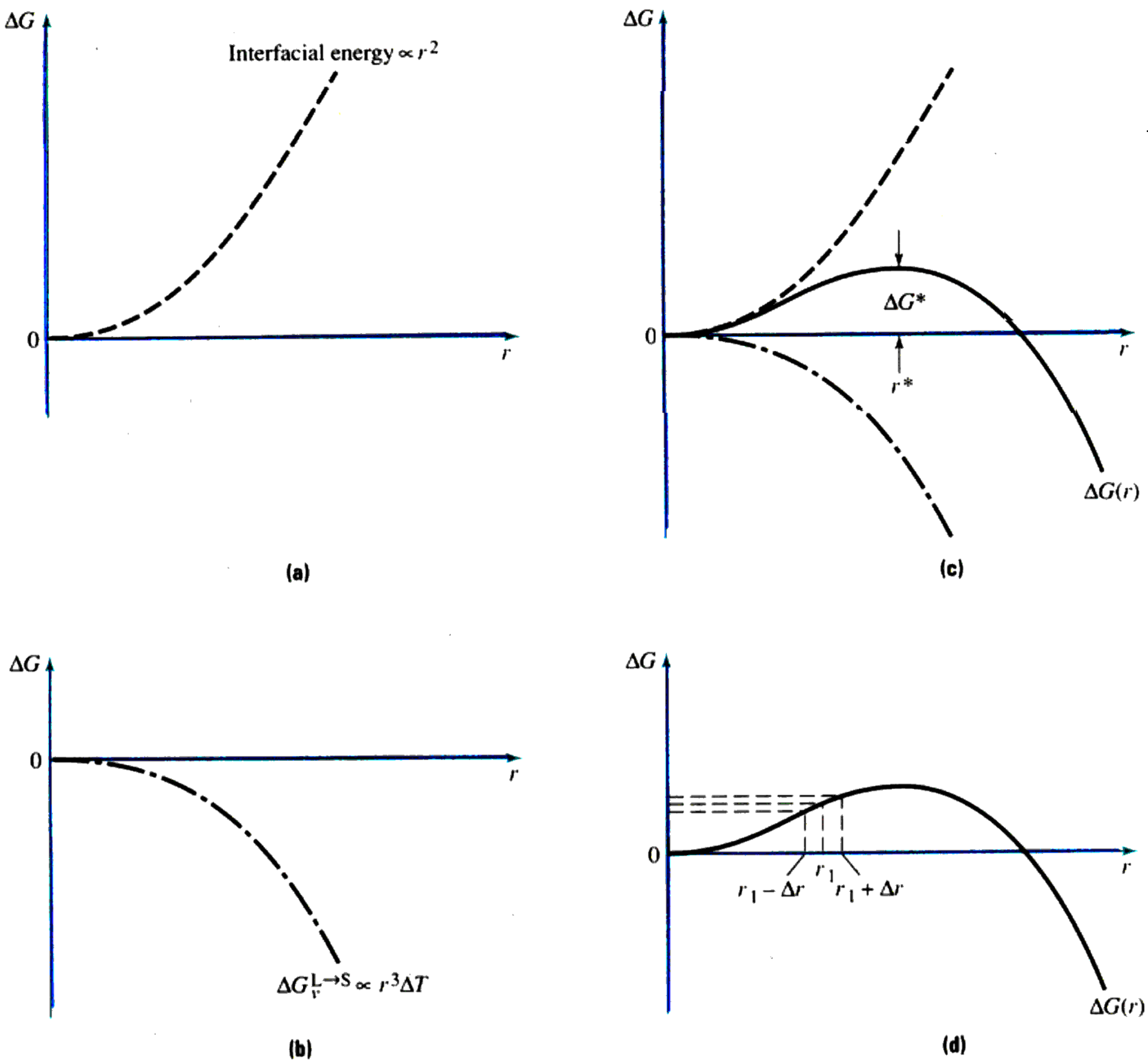
  additional energy- interfacial energy
- undercooling→ energy available to create the phase boundary

Phase Transformation

- nucleation: homogeneous or heterogeneous
- growth



Homogeneous Nucleation



Assumption
- isotropic interface energy
- independent of size
- spherical nucleus

Homogeneous Nucleation

- change in free energy as a function of *r*

$$\Delta G(r) = (\tfrac{4}{3}\pi r^3)\Delta G_V + (4\pi r^2)\gamma_{SL}$$

- critical radius r*

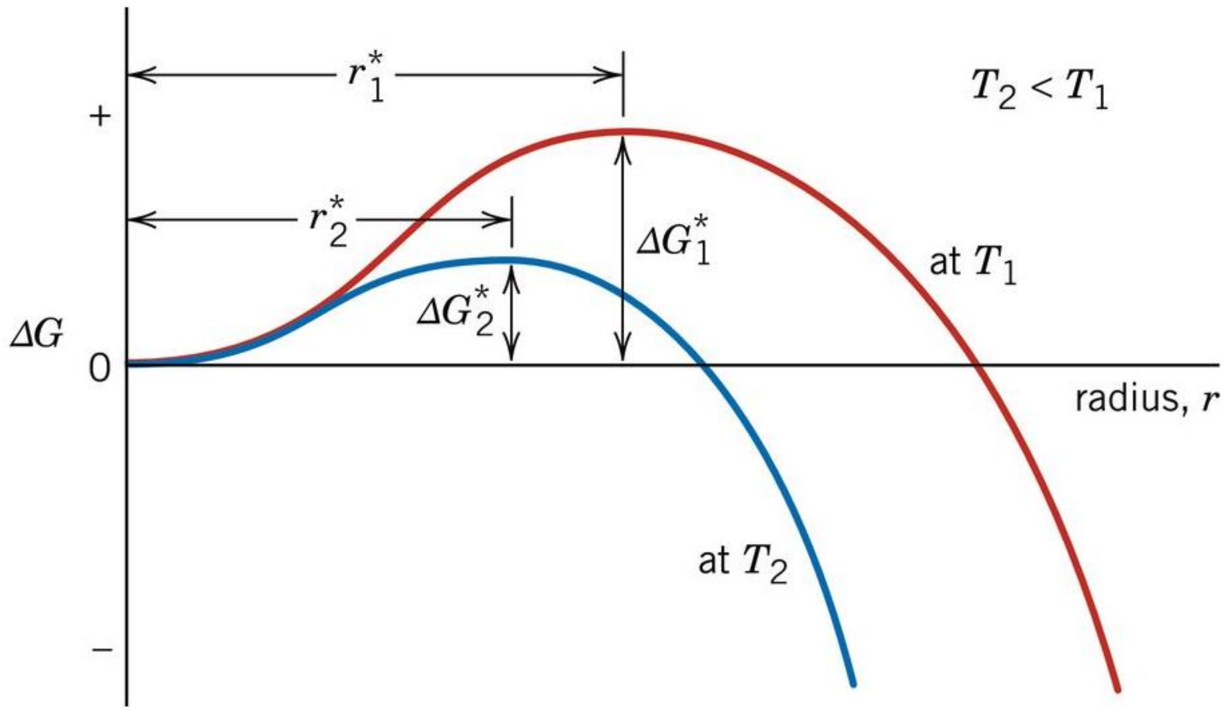
$$\frac{d[\Delta G(r)]}{dr} = 0 = 4\pi r^2 \Delta G_V + 8\pi r_{SL}$$

$$r^* = \frac{-2r_{SL}}{\Delta G_V} = \frac{-2\gamma_{SL} T_E}{\Delta H_V \Delta T}$$ (r^* decreases as undercooling increases)

- $\Delta G^* = \dfrac{16\pi\gamma_{SL}^3 T_E^2}{3\Delta H_V^2}\dfrac{1}{\Delta T^2}$ (energy barrier decreases

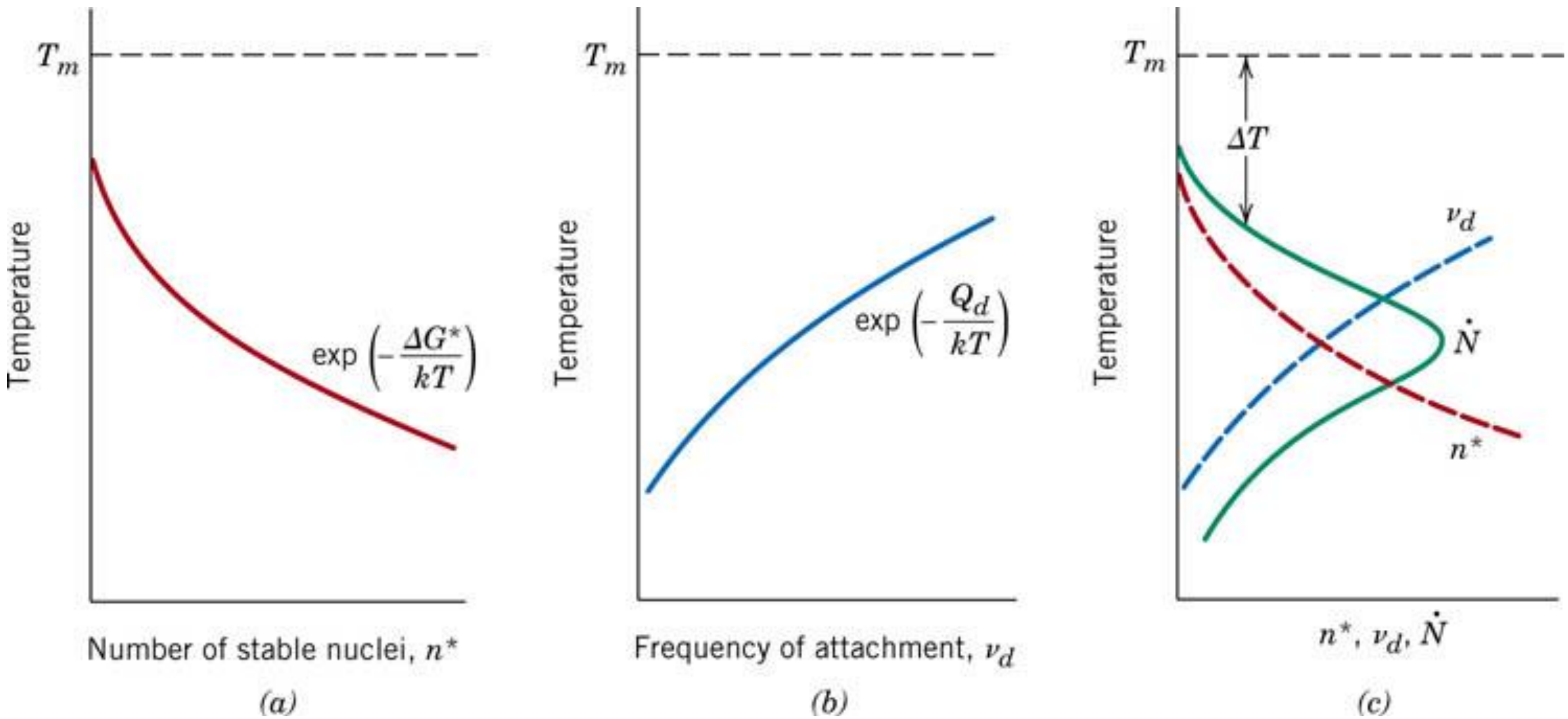
as undercooling increases)

Homogeneous Nucleation



Homogeneous Nucleation

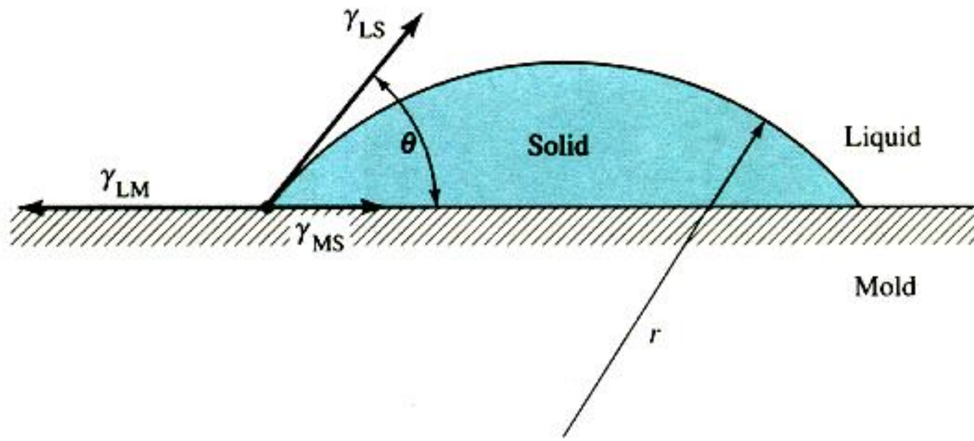
- for nucleation, atomic mobility should be considered in addition to nucleation barrier term

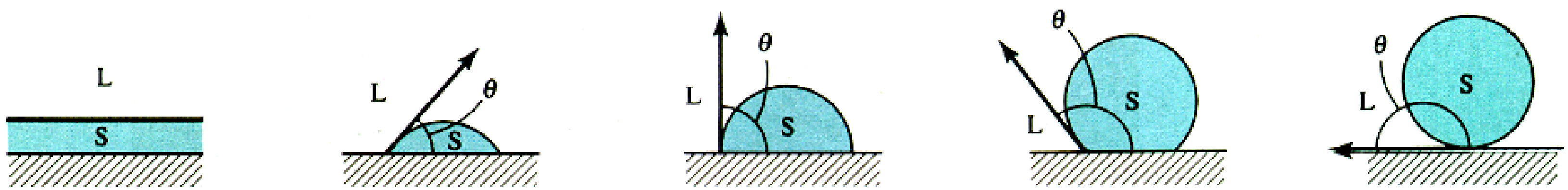


Heterogeneous Nucleation

$$\gamma_{LM} = \gamma_{MS} + \gamma_{LS}\cos\theta$$

θ: contact angle





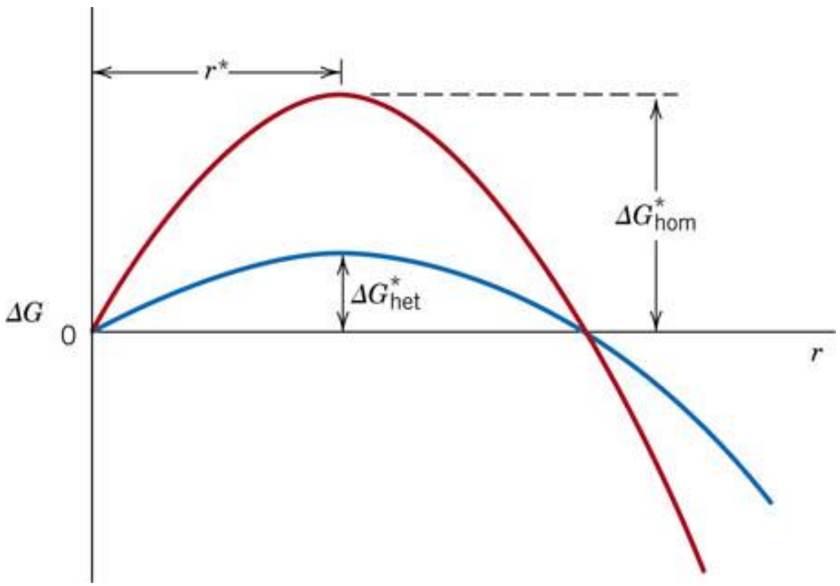
Complete wetting. No barrier to nucleation.

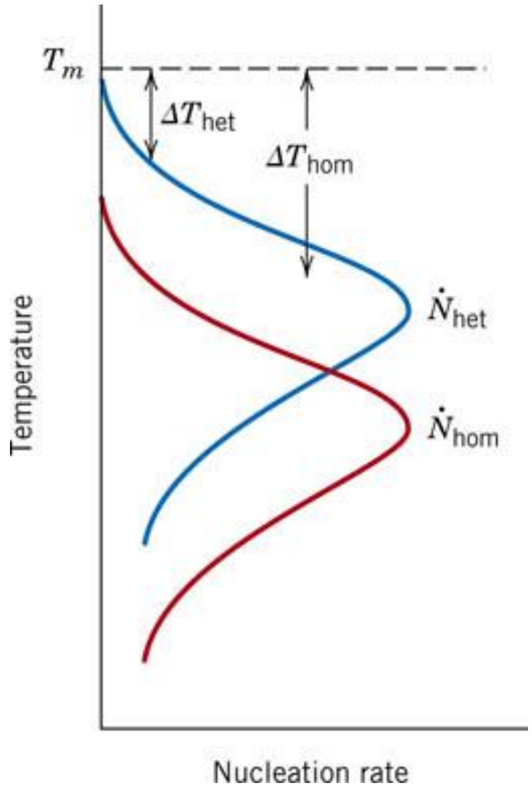
No wetting. Nucleation indistinguishable from homogeneous nucleation.

$\theta = 0$	$\pi/4$	$\pi/2$	$3\pi/4$	π
$f(\theta) = 0$	0.058	0.500	0.943	1.000

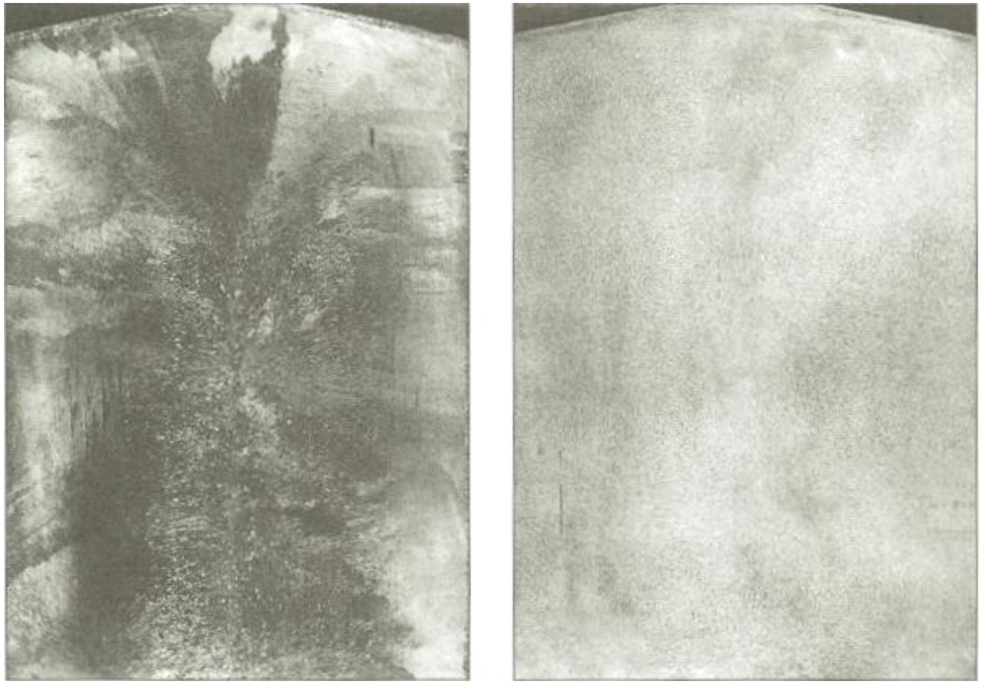
Heterogeneous Nucleation

- $\Delta G^{*}_{het} \propto \Delta G^{*}_{\hom} f(\theta), \quad 0 < f(\theta) < 1$
- energy barrier for heterogeneous nucleation is always lower than that for homogeneous nucleation





Heterogeneous Nucleation



cast aluminum alloy

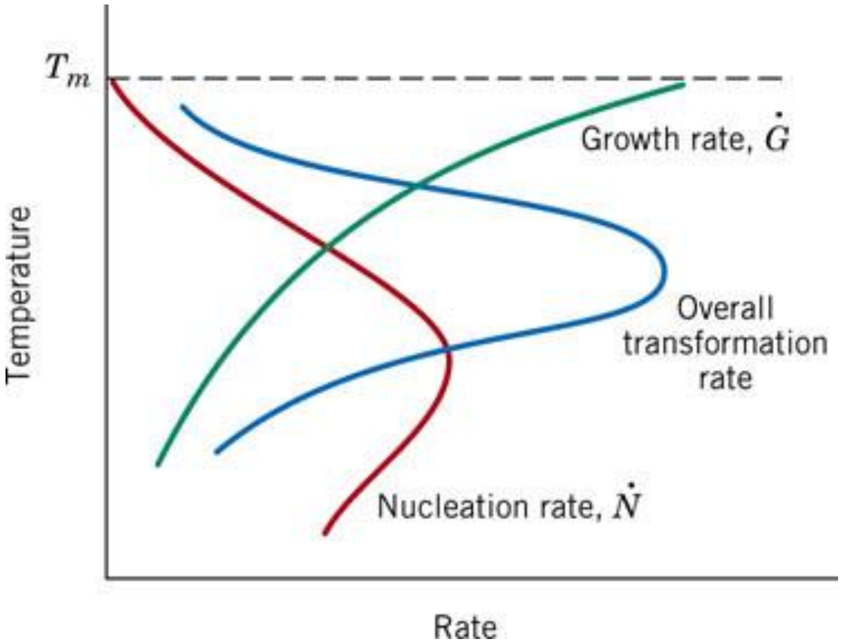
grain refiner (TiB_2)

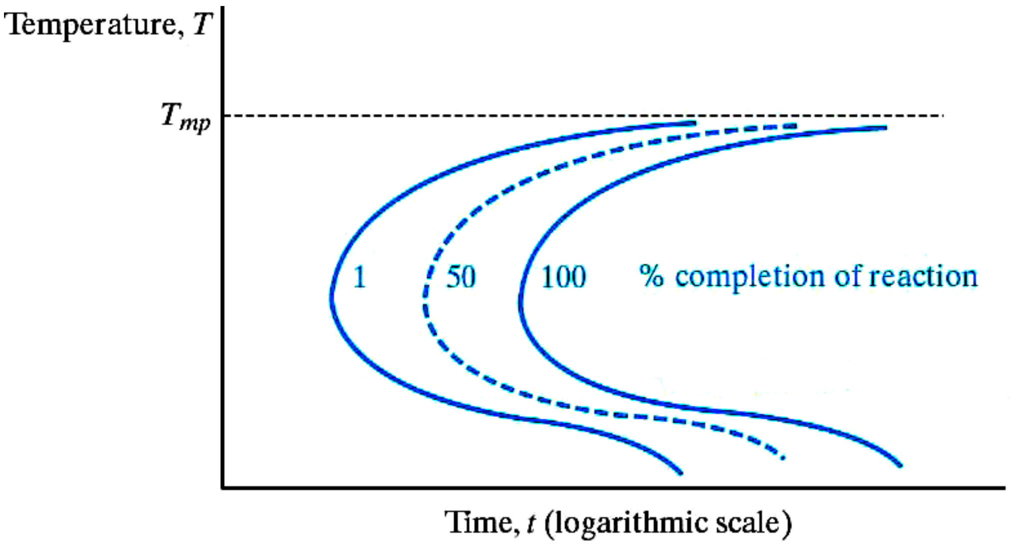
Growth

- growth process is diffusional in nature

$$\dot{G} = Ce^{-Q/RT}$$

- overall transformation rate



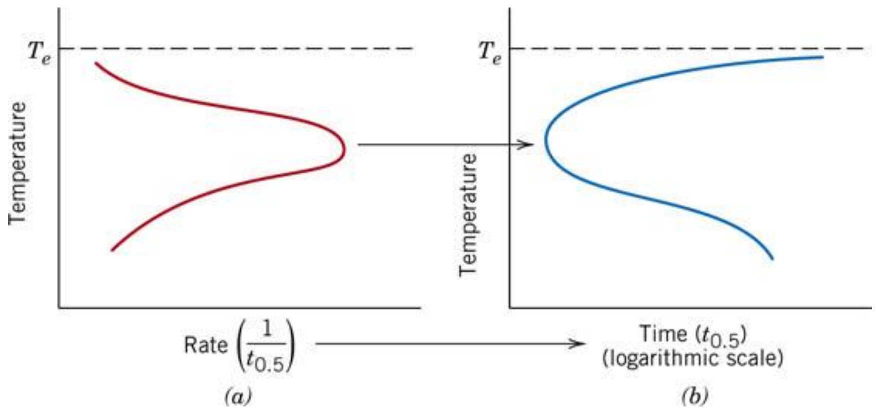


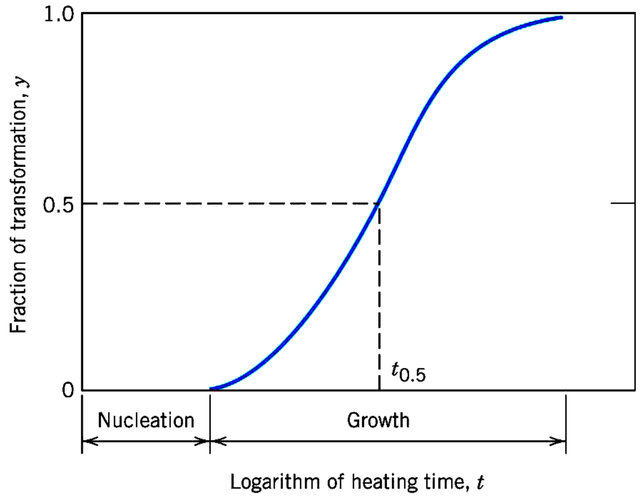
TTT diagram

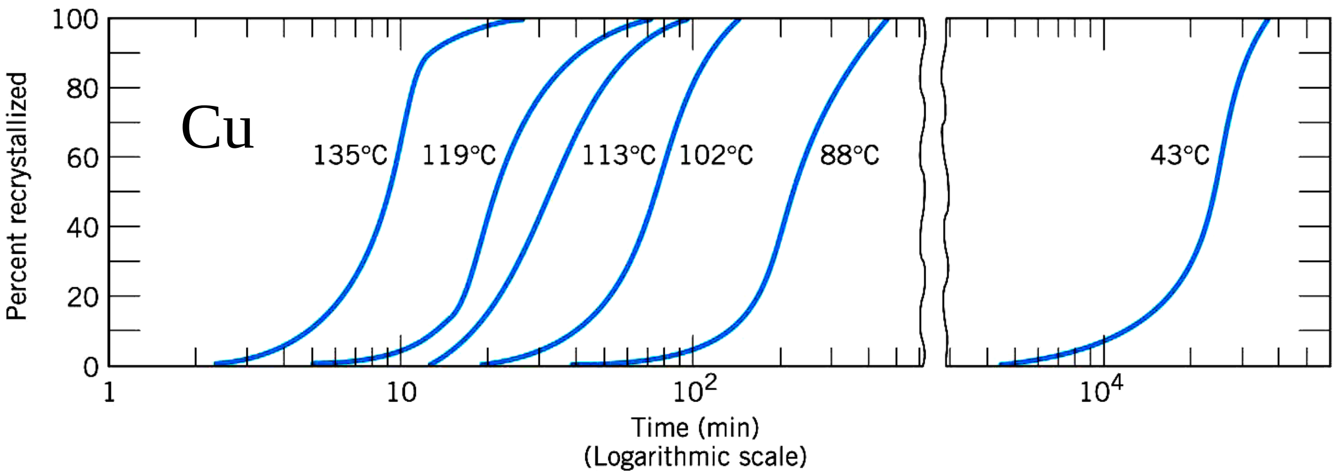
Phase Transformation

fraction of transformation

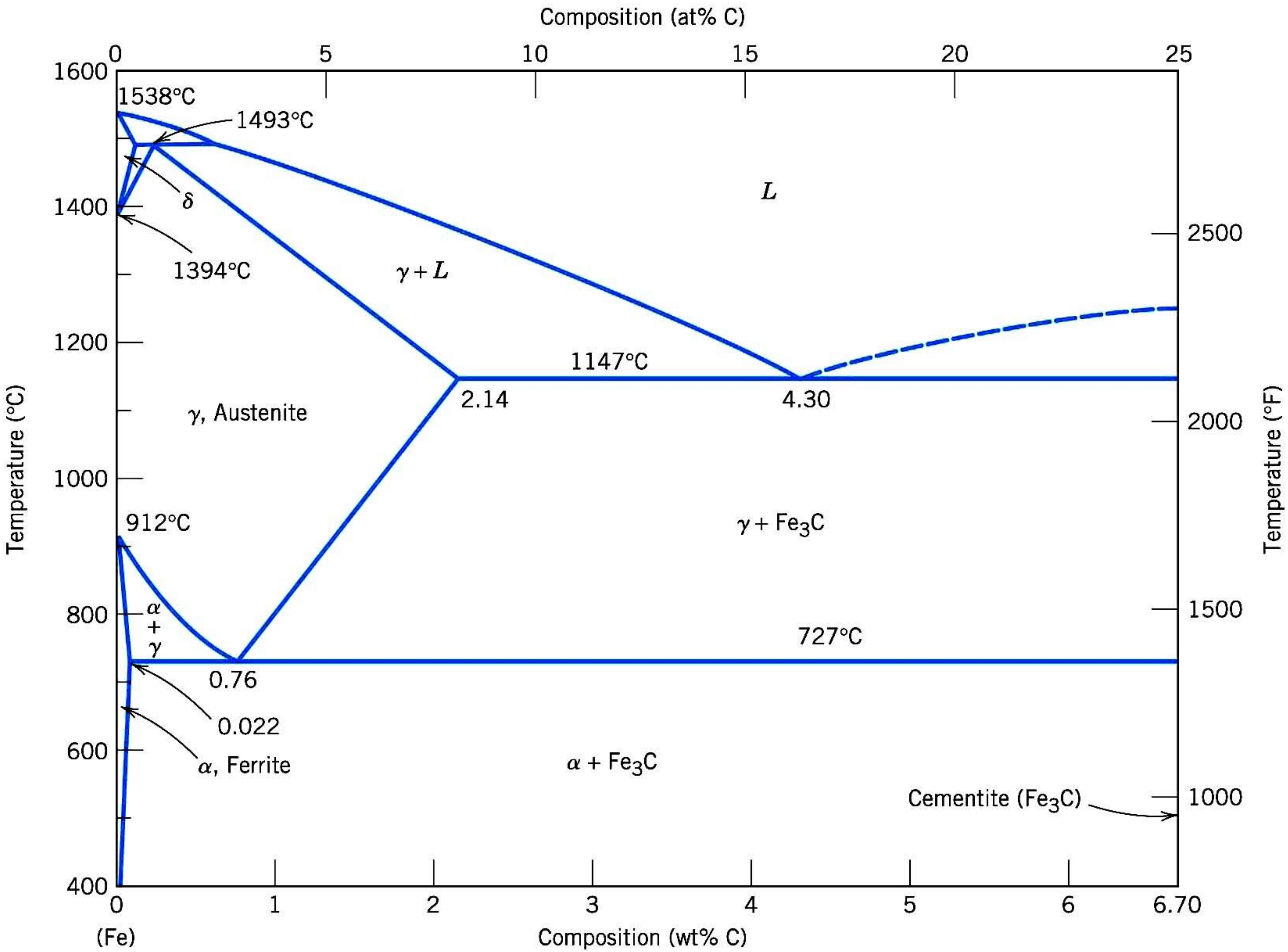
$$y = 1 - \exp(-kt^n)$$



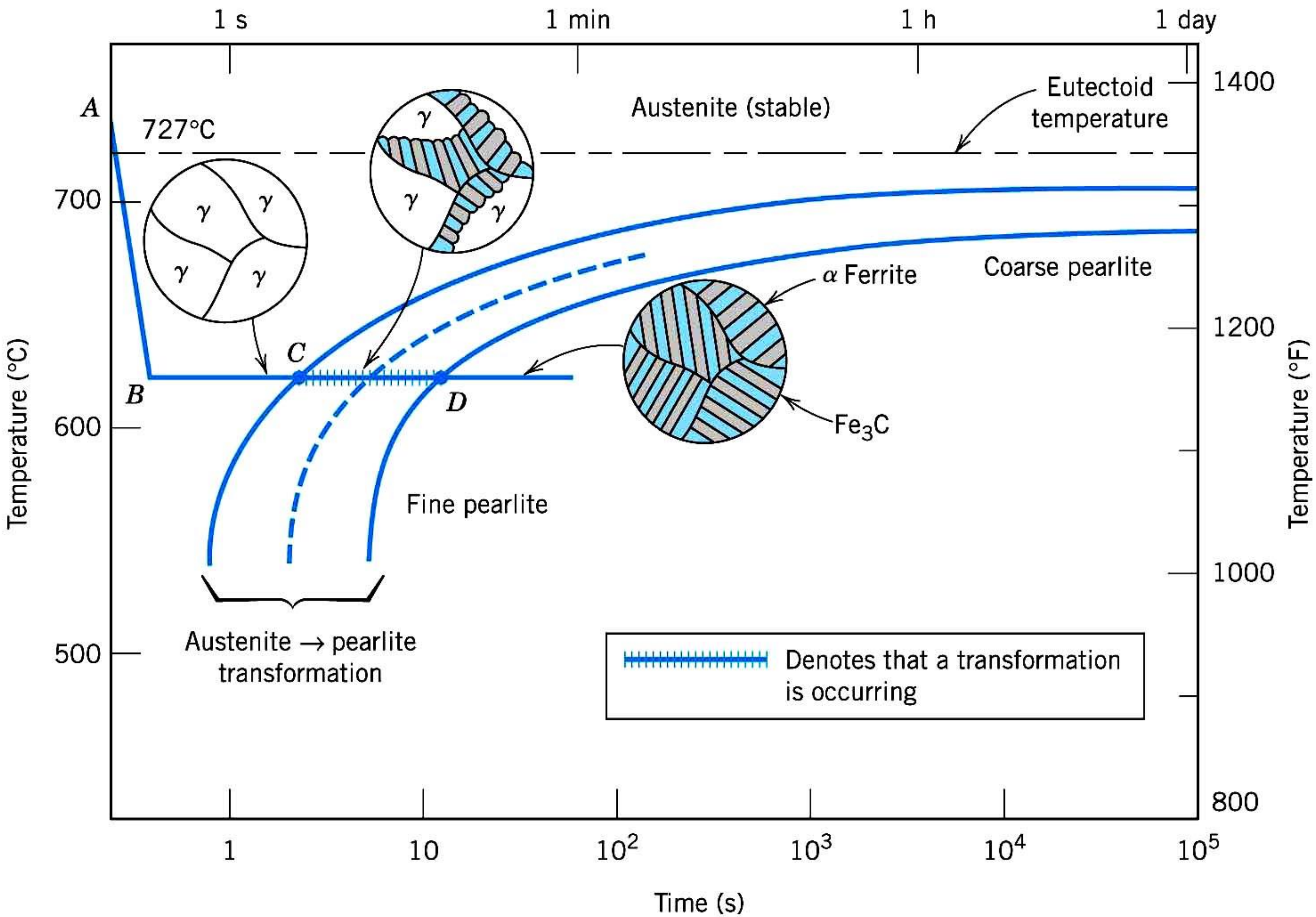




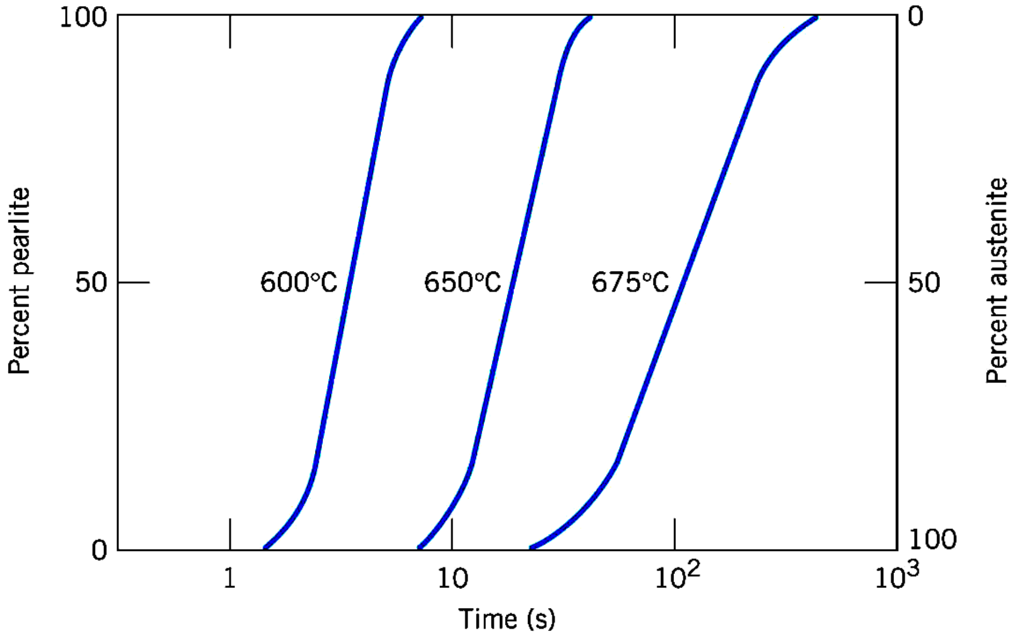
Fe–Fe_3C System

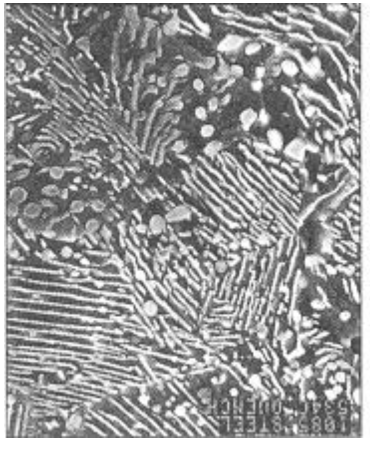


Isothermal Transformation Diagram

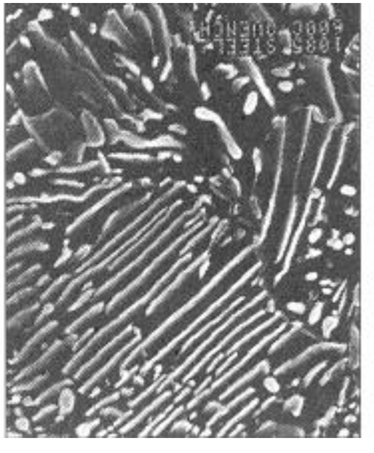


Eutectoid Steel

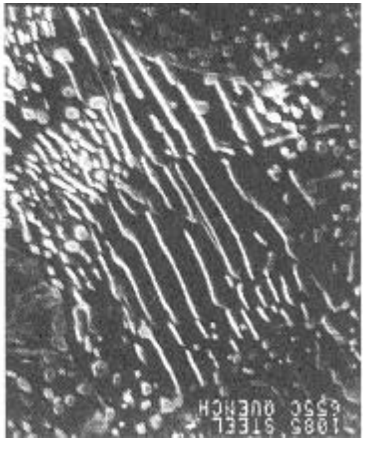




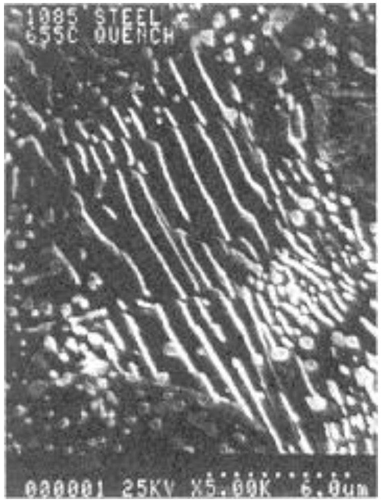
534°C



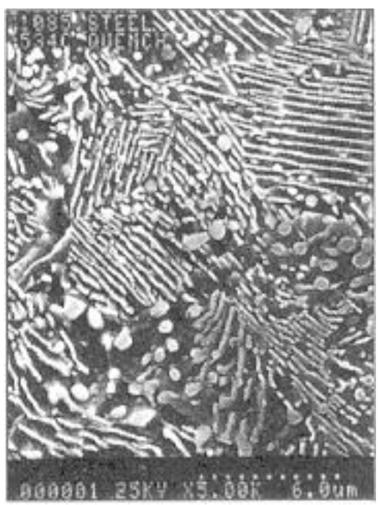
600°C



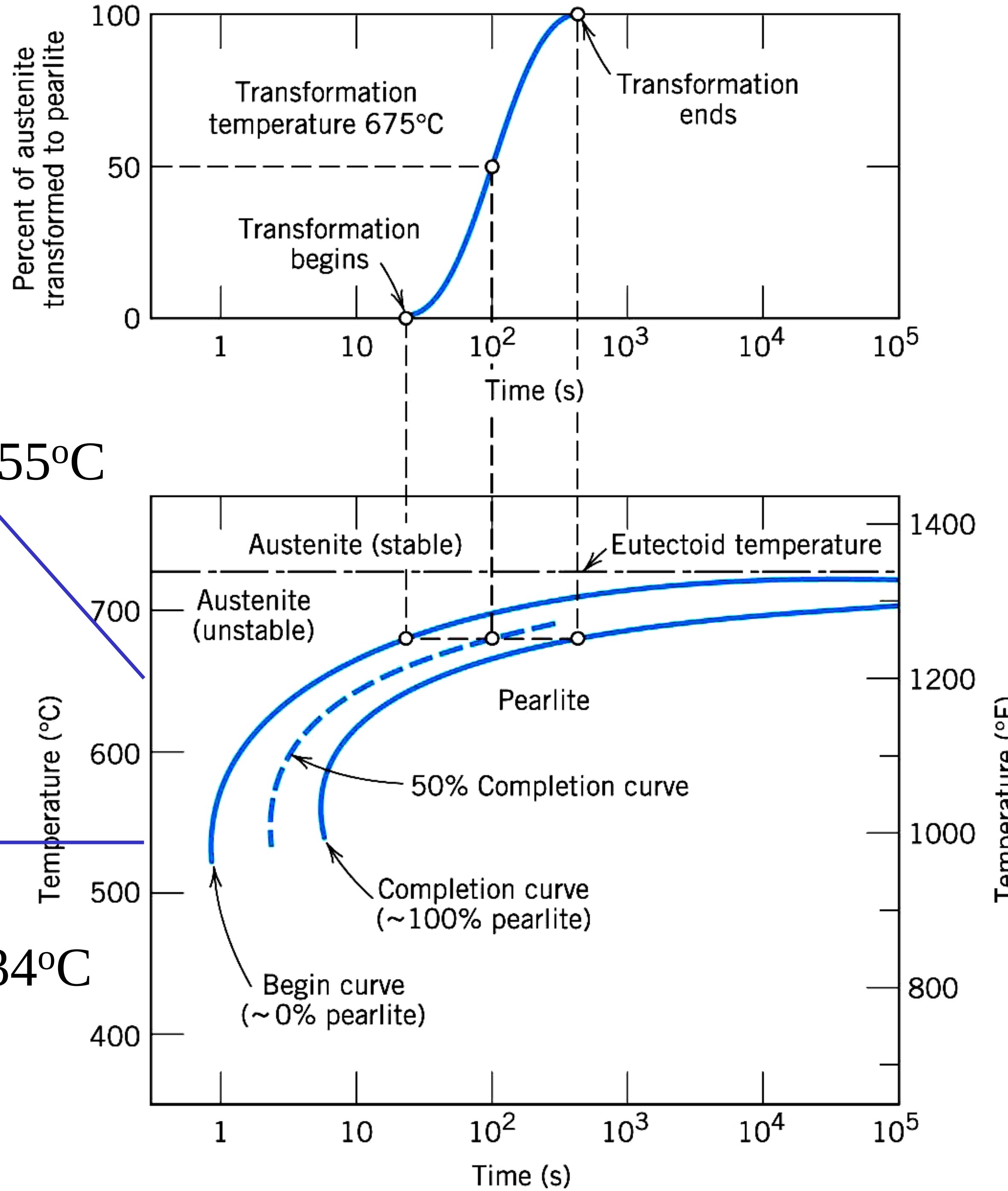
655°C

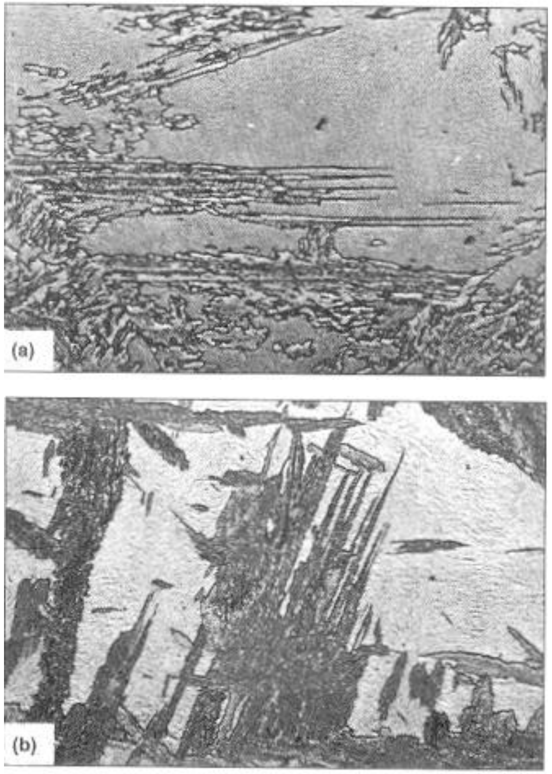

1085 STEEL
655C QUENCH
000001 25KV X5.00K 6.0um

655°C

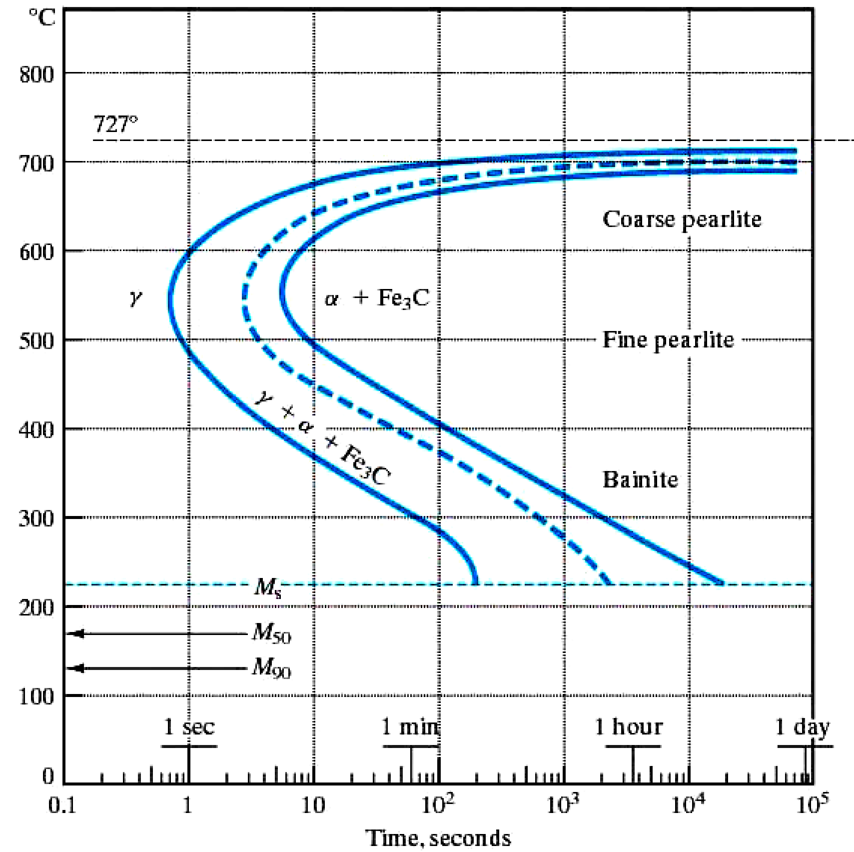

1085 STEEL
534C QUENCH
000001 25KV X5.00K 6.0um

534°C


Percent of austenite transformed to pearlite
100
50
0
Transformation temperature 675°C
Transformation ends
Transformation begins
1
10
10^2
10^3
10^4
10^5
Time (s)
Austenite (stable)
Eutectoid temperature
Austenite (unstable)
Pearlite
50% Completion curve
Completion curve (~100% pearlite)
Begin curve (~0% pearlite)
Temperature (°C)
700
600
500
400
Temperature (°F)
1400
1200
1000
800

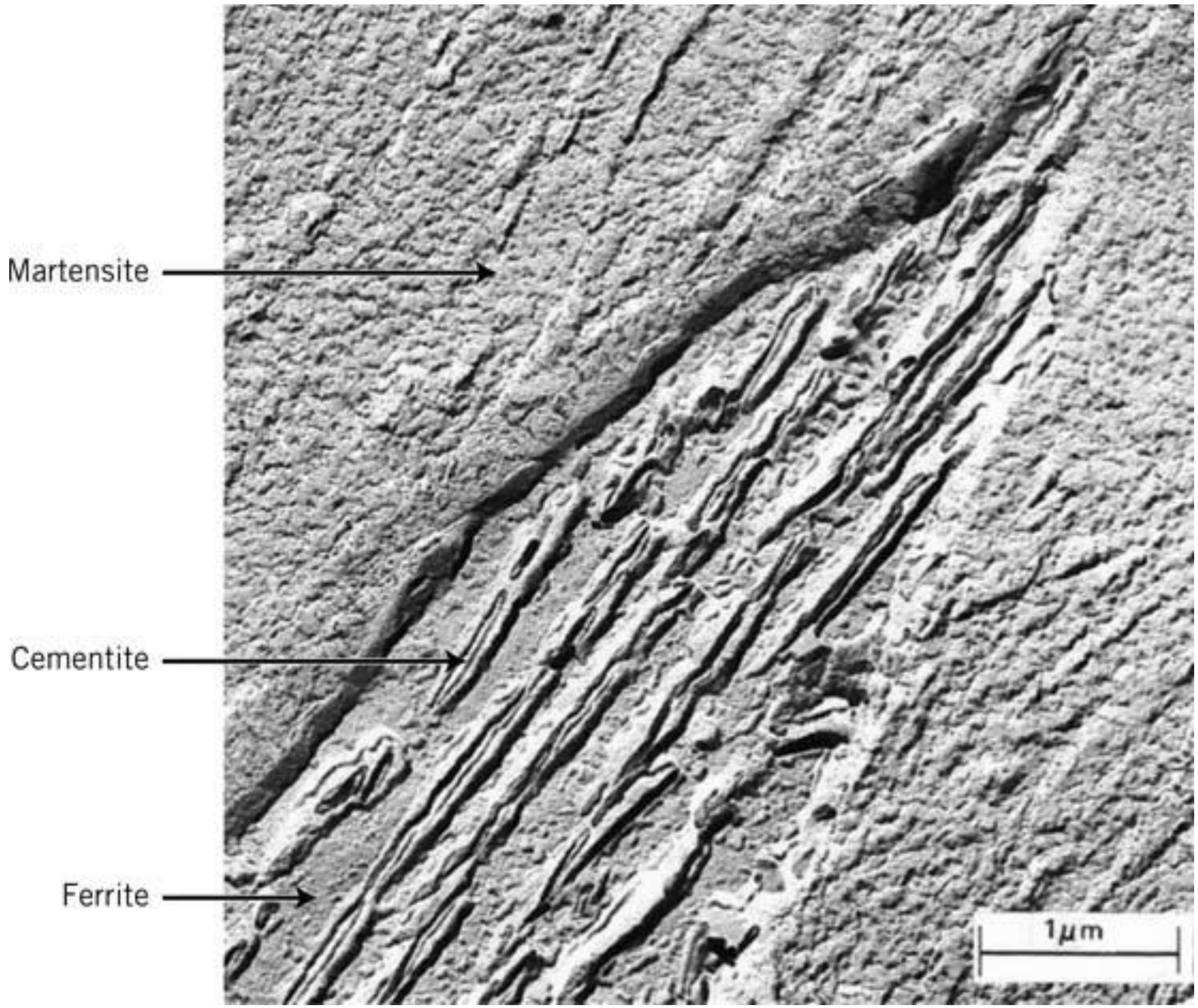


bainite



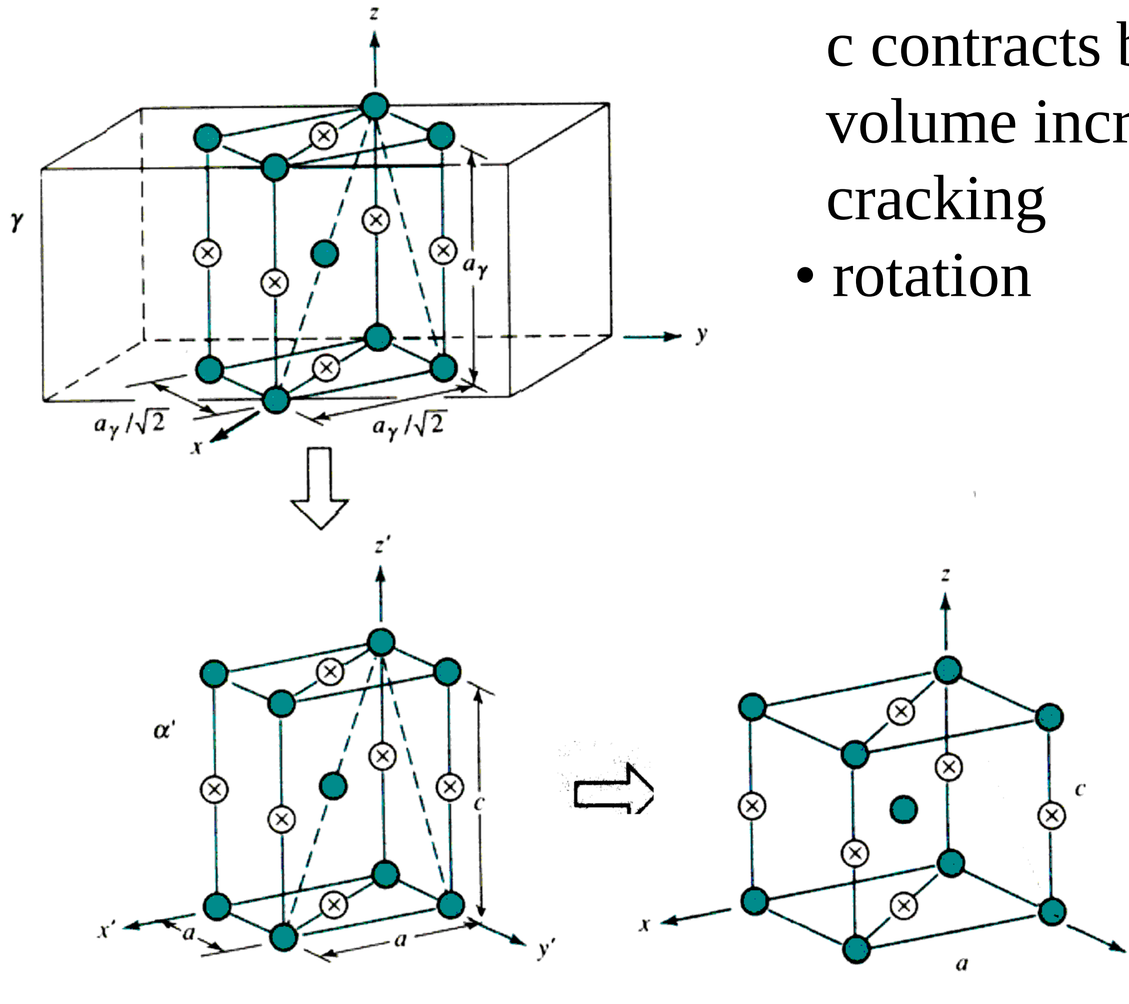
(a) (b) (c)

martensite
habit plane
habit direction

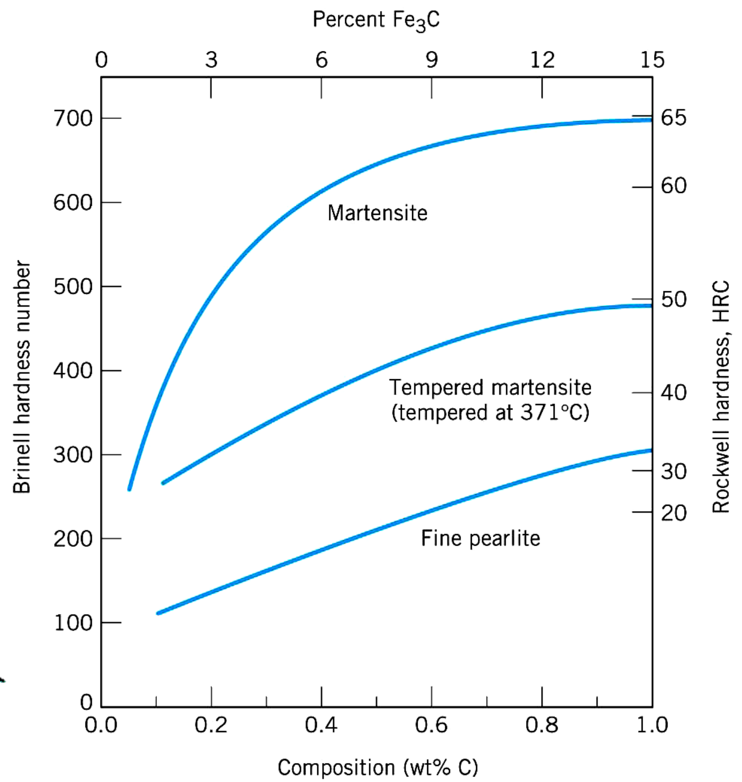

Martensite
Cementite
Ferrite
1μm

Martenstic Transformation

- FCC→ BCT
- bain distortion
  c contracts by 20%, a expands by 12%
  volume increases, internal stress
  cracking
- rotation

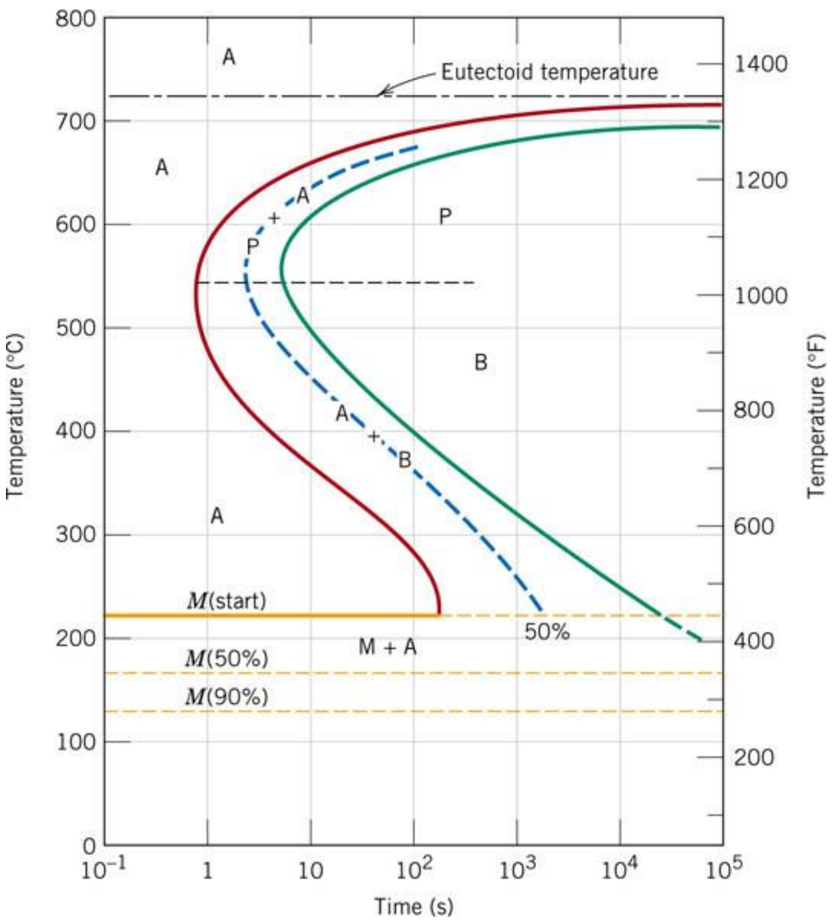


c/a ≃ 1.4

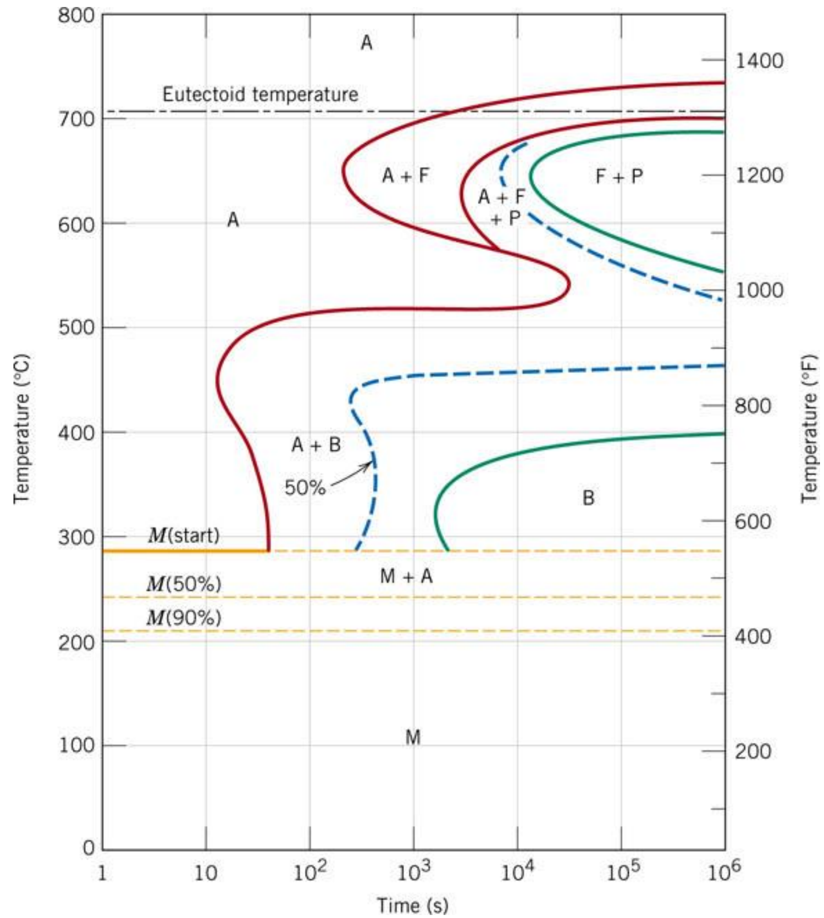


Effect of Alloying Elements

Cr, Ni, Mo, W

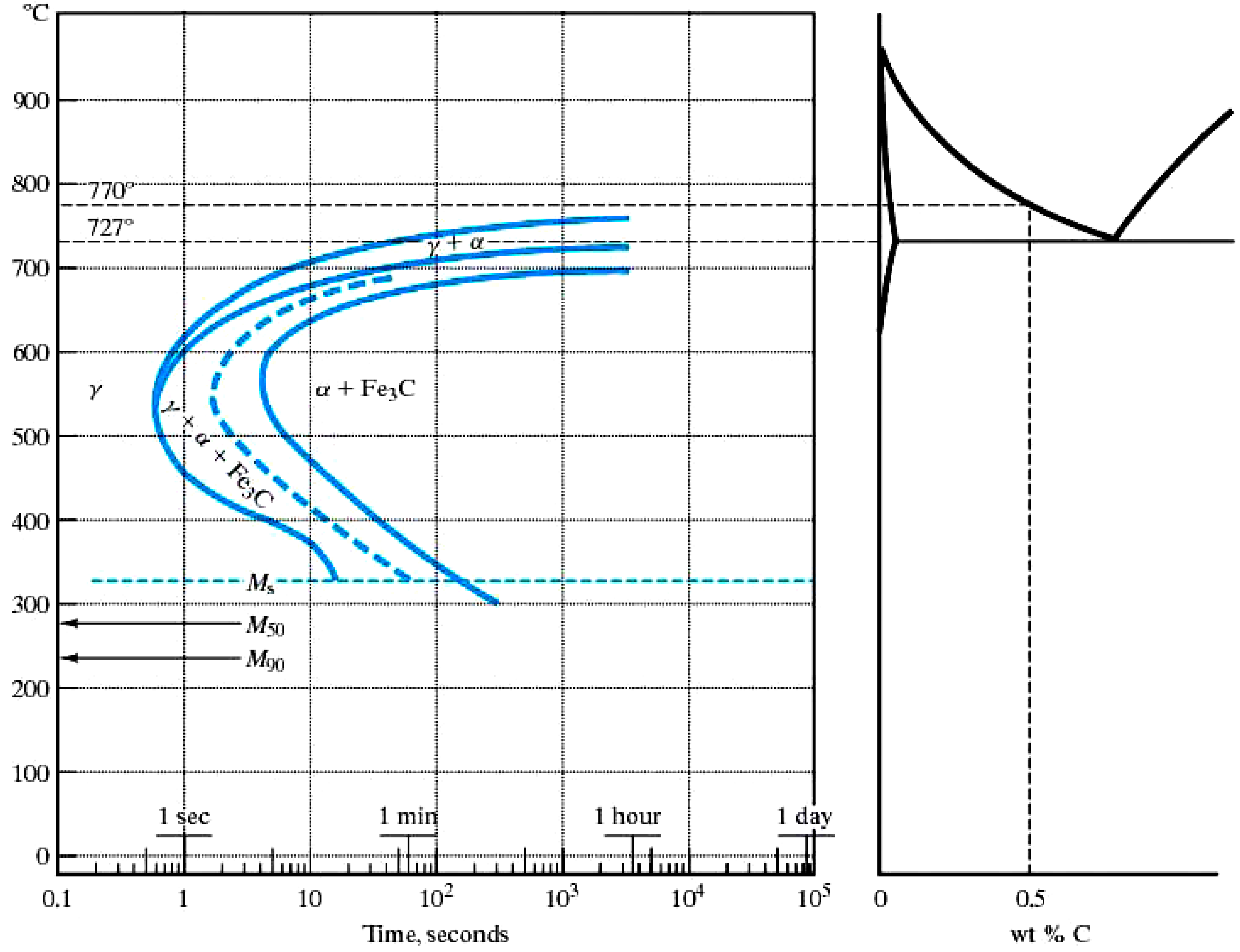


plain carbon steel

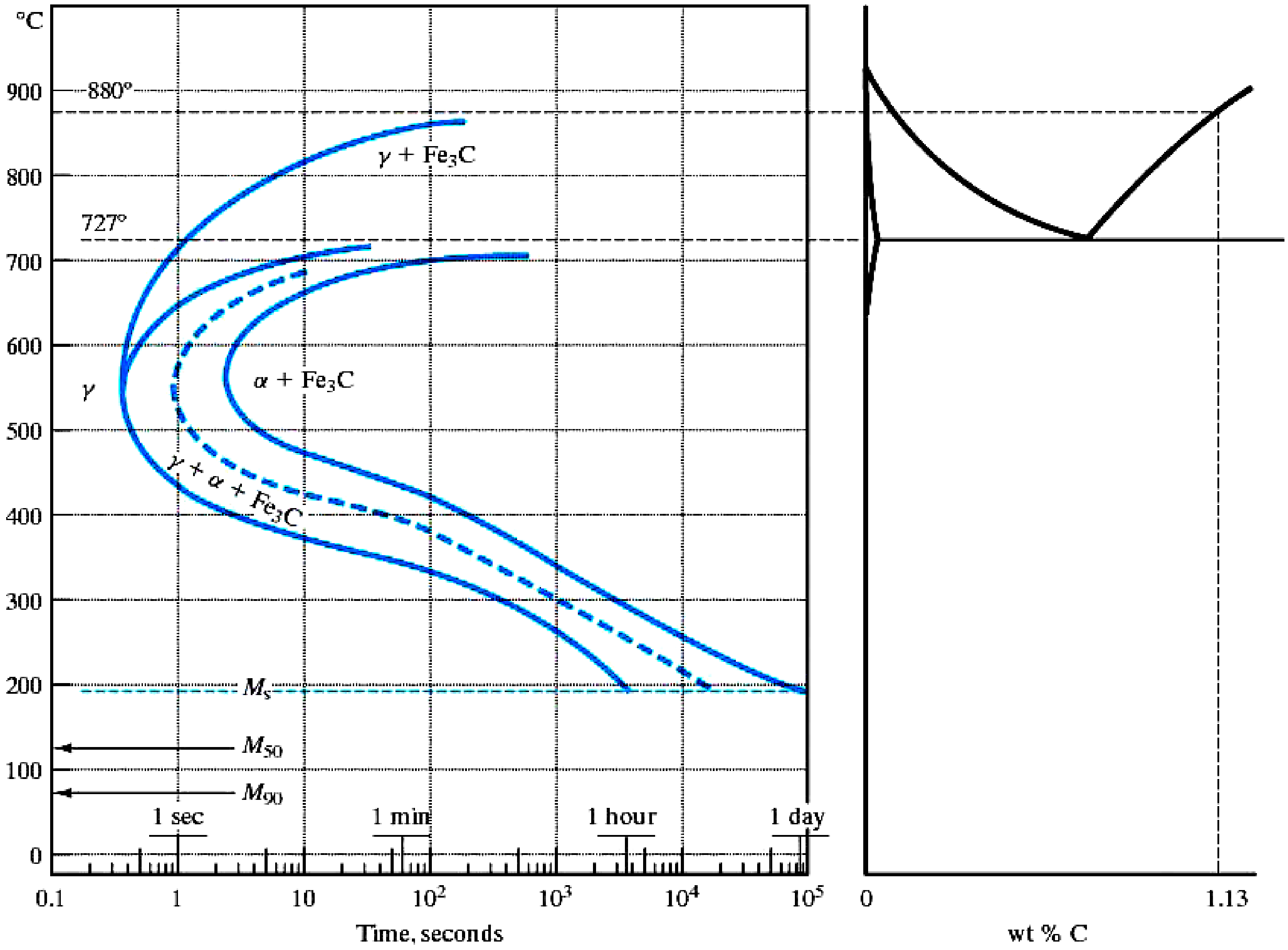


4340 alloy steel

Hypoeutectoid

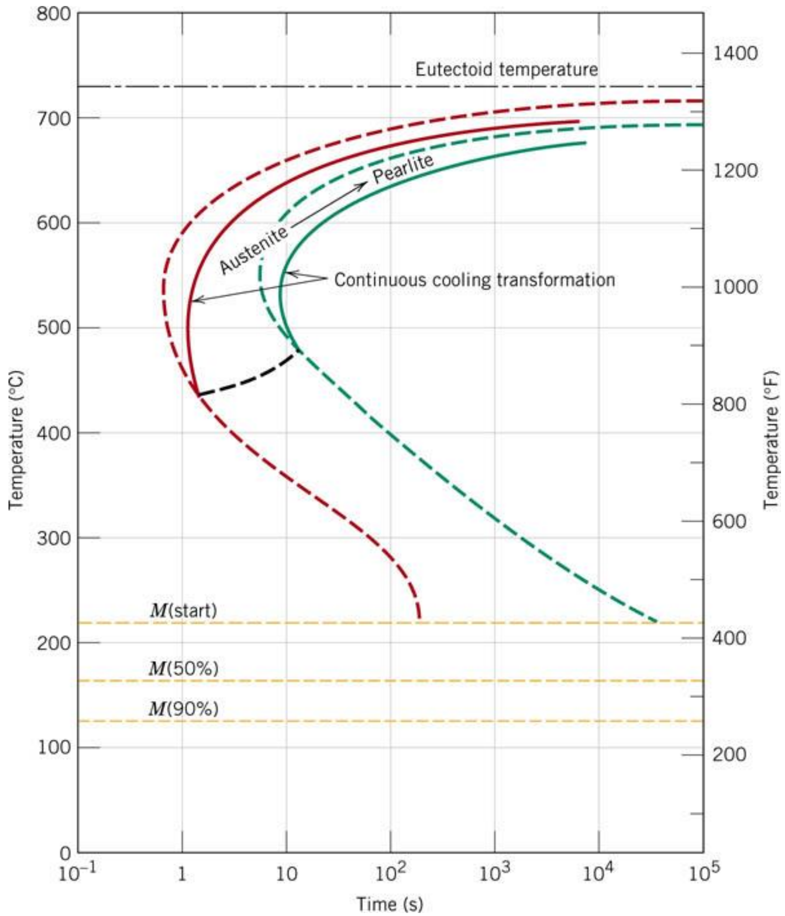


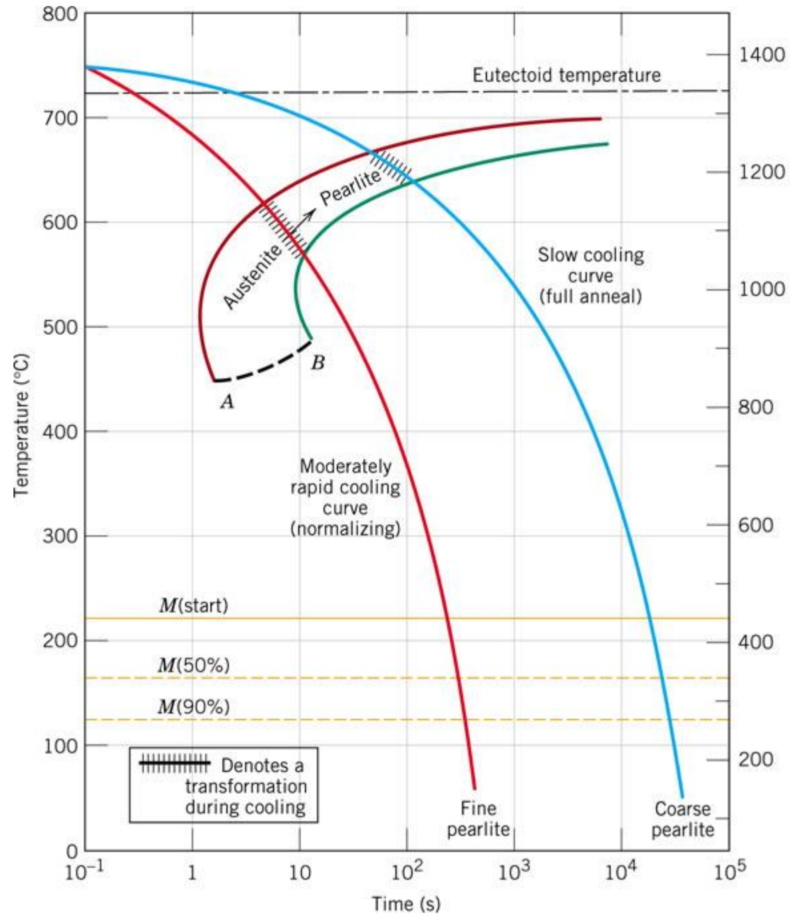
Hypereutectoid



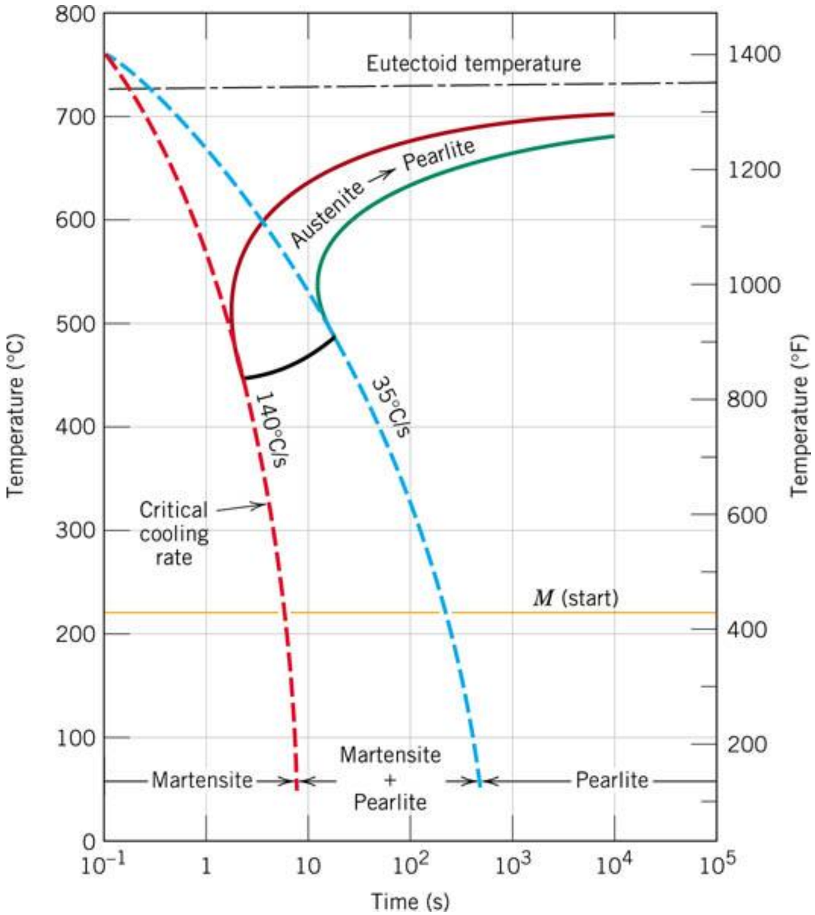
Continuous Cooling Transformation

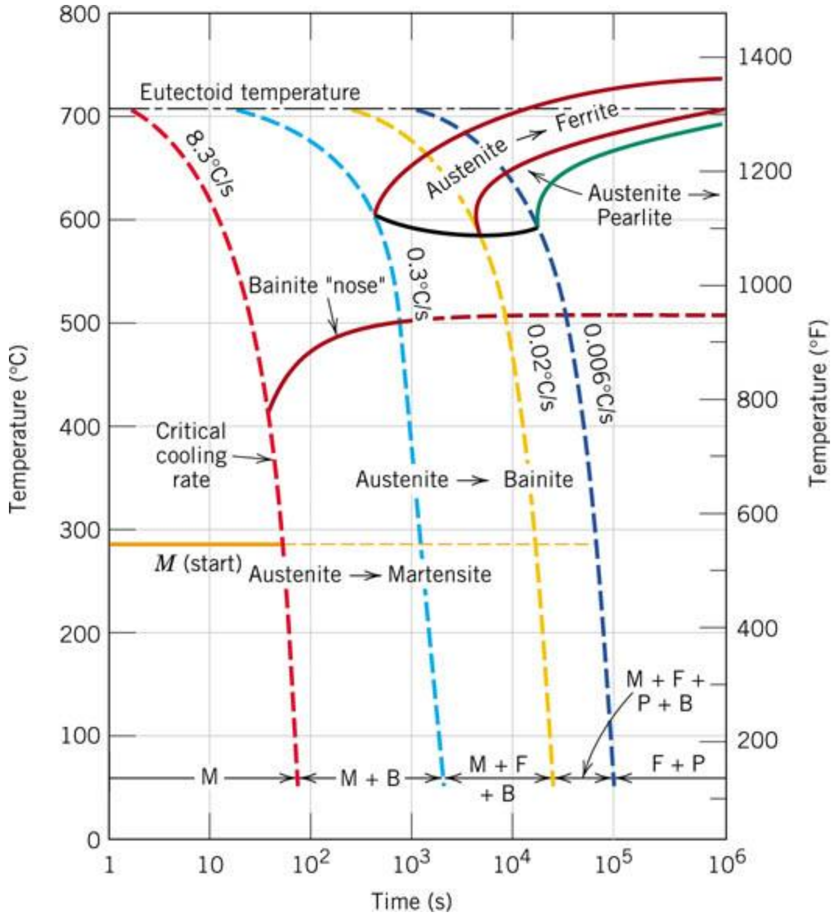
- to shift transformation curve downward and toward the right





Continuous Cooling Transformation

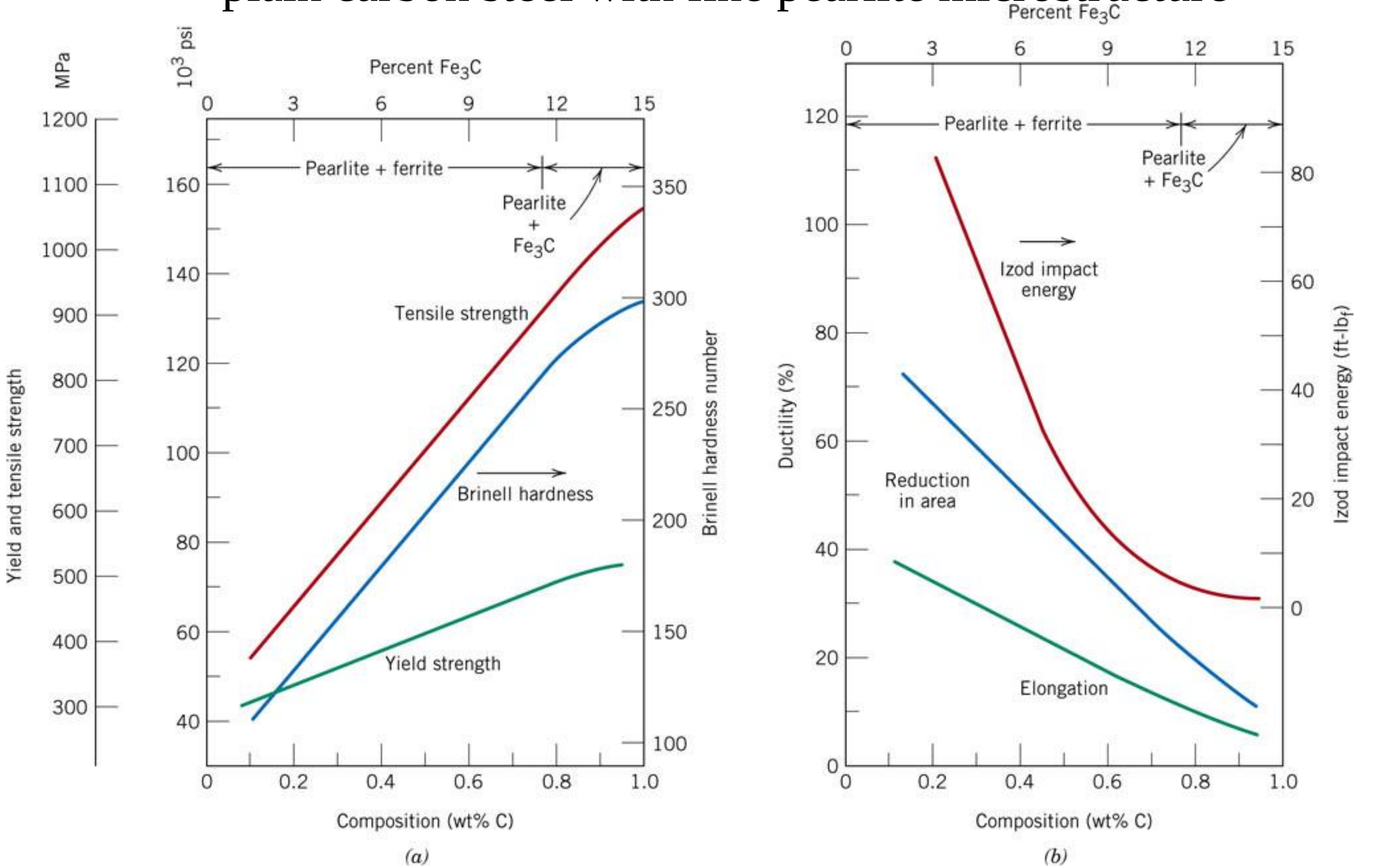




4340 alloy steel

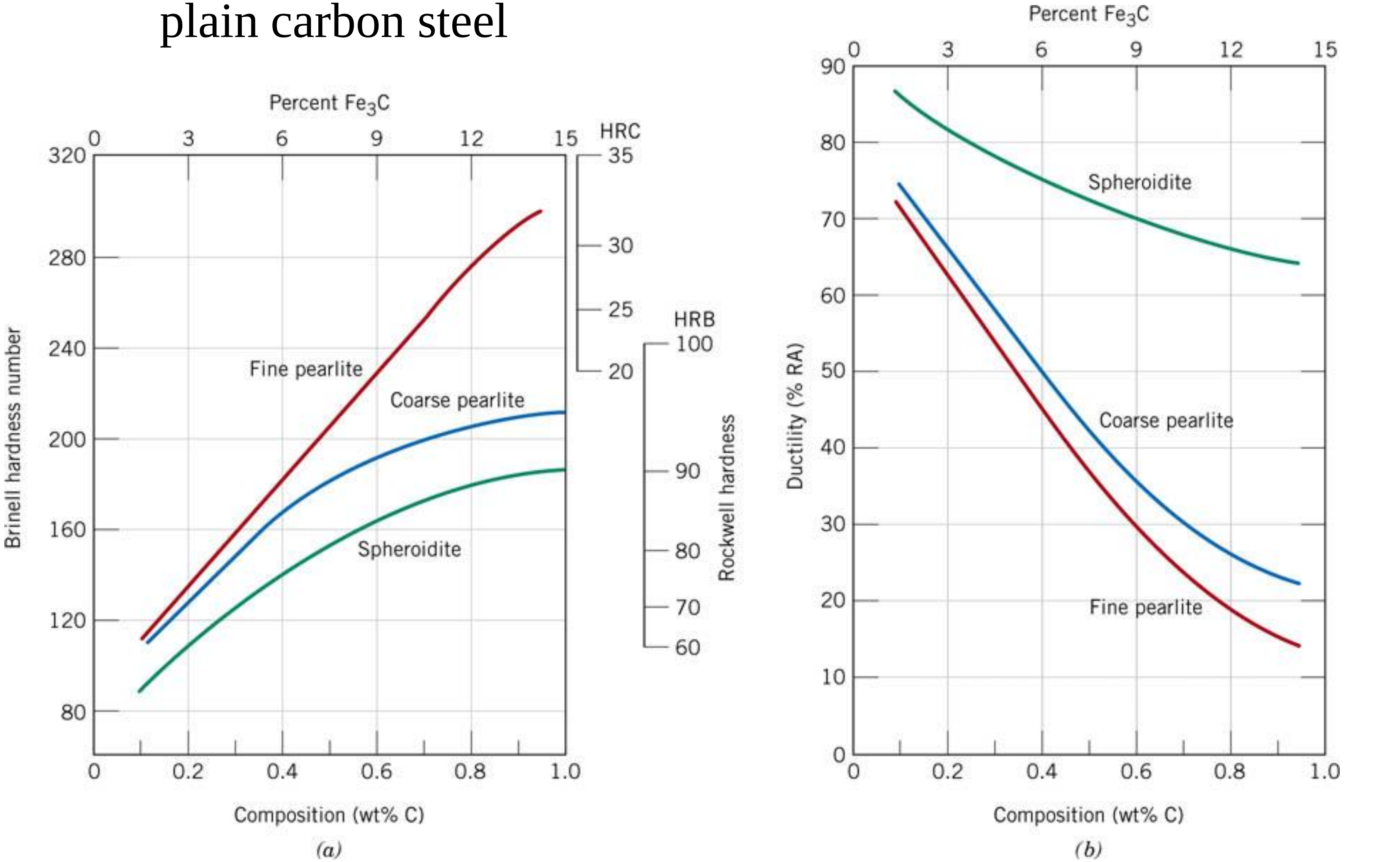
Mechanical Properties

plain carbon steel with fine pearlite microstructure



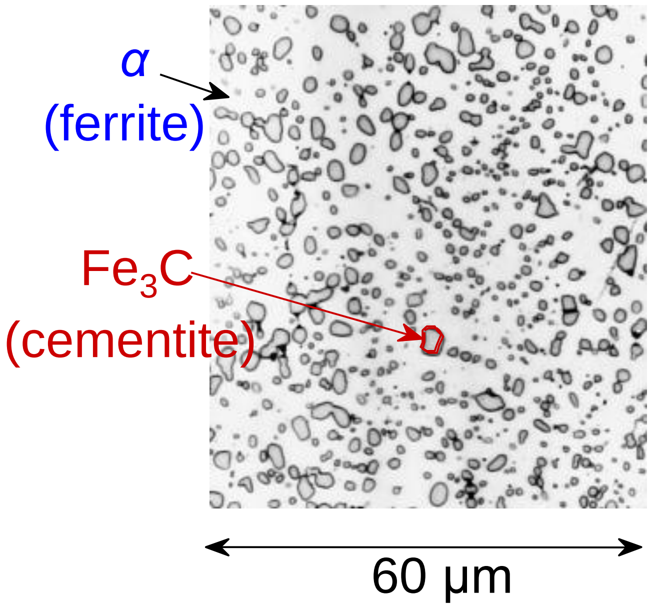
Mechanical Properties

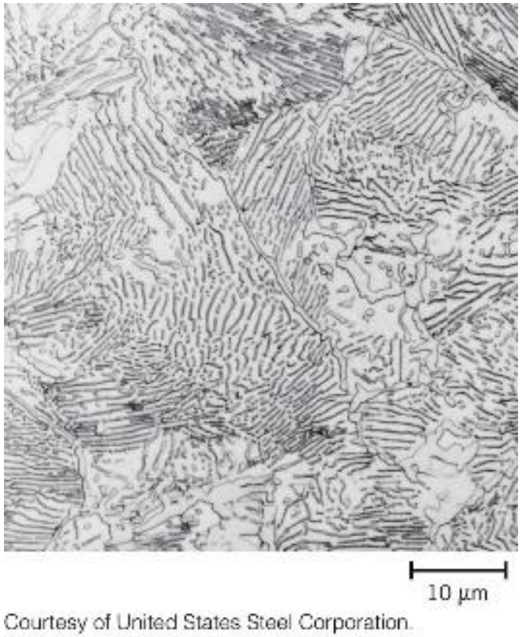
plain carbon steel



Spheroidite: Another Microstructure for the Fe-Fe_3C System

- Spheroidite:
  - -- Fe_3C particles within an α-ferrite matrix
  - -- formation requires diffusion
  - -- heat bainite or pearlite at temperature just below eutectoid for long times
  - -- driving force – reduction of α-ferrite/Fe_3C interfacial area

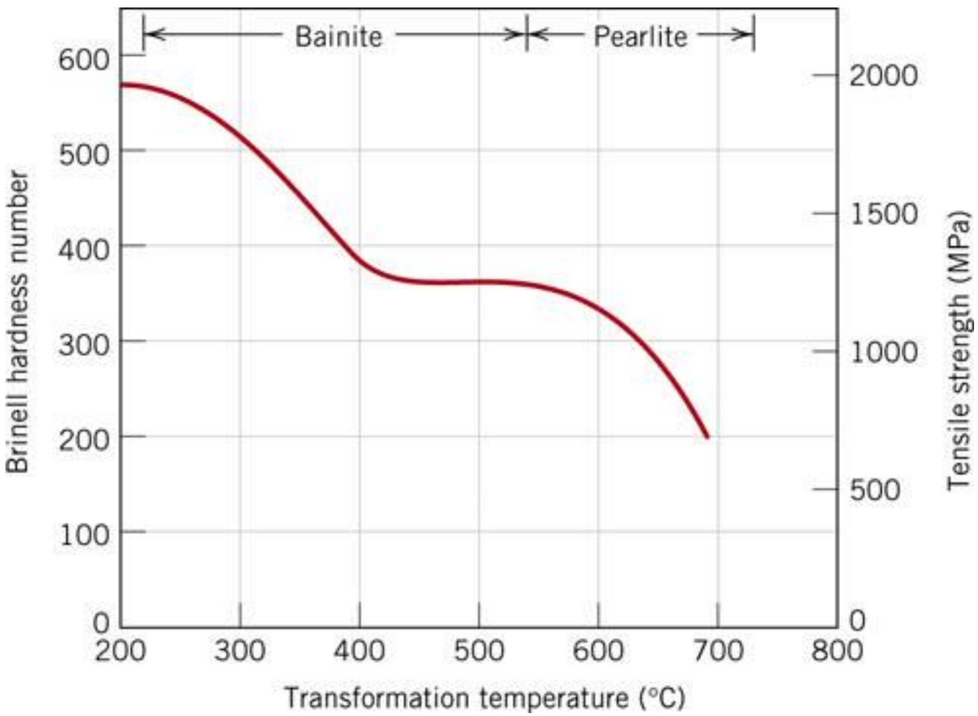




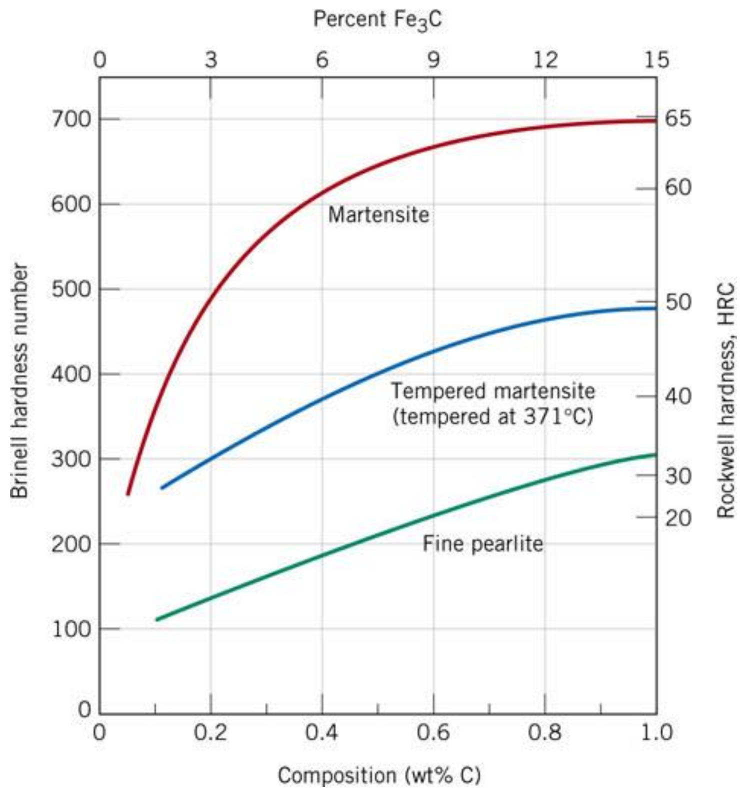
partially transformed to spheroidite

Mechanical Properties

plain carbon steel

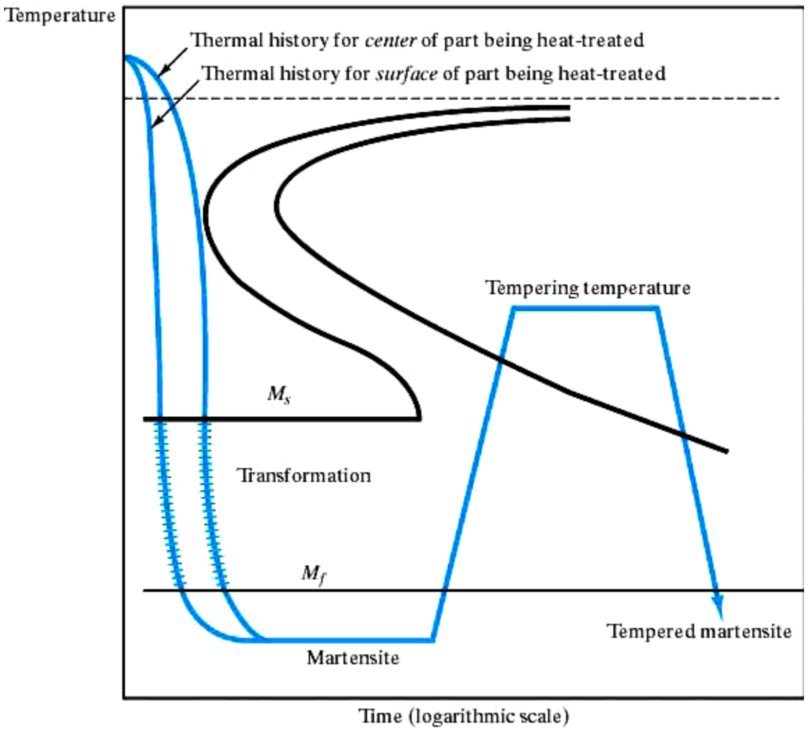


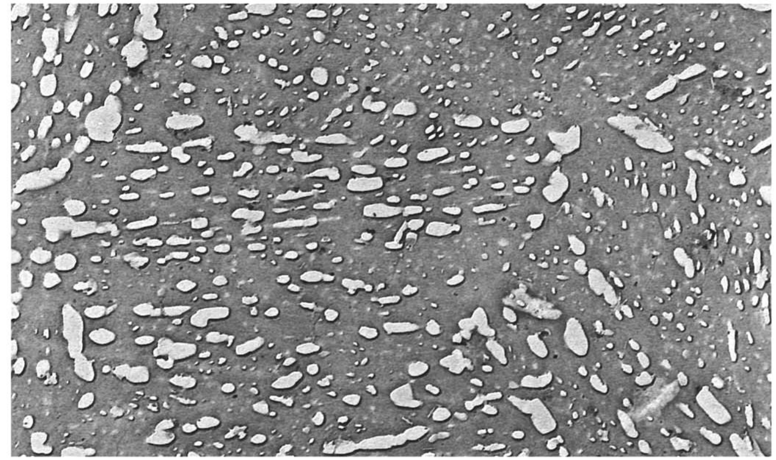
eutectoid composition



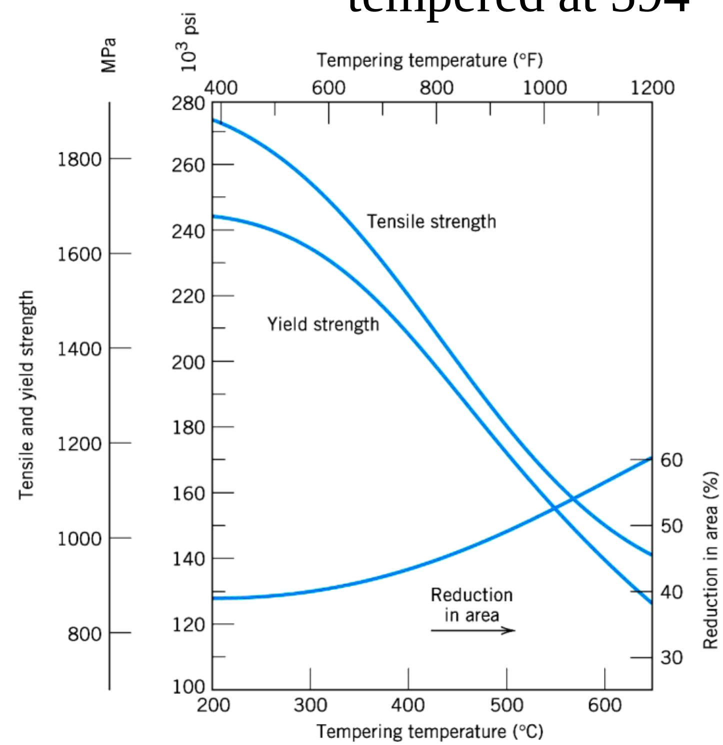
plain carbon steel

Tempering

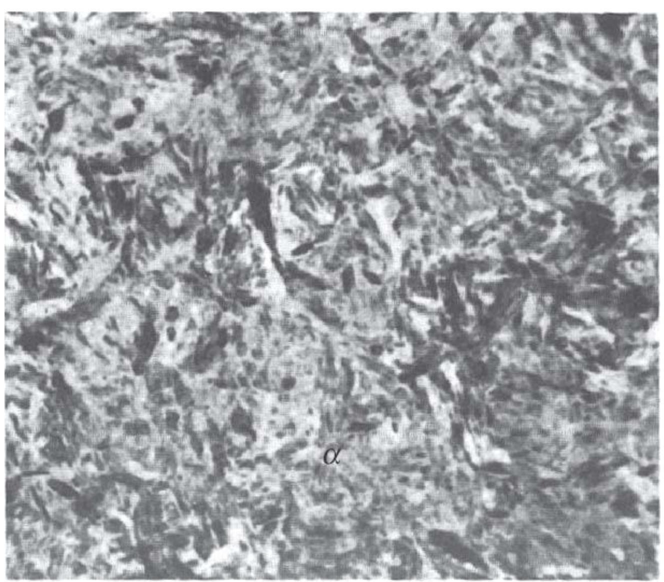




tempered at 594 °C



oil quenched alloy steel 4340 type



0.5 wt% C

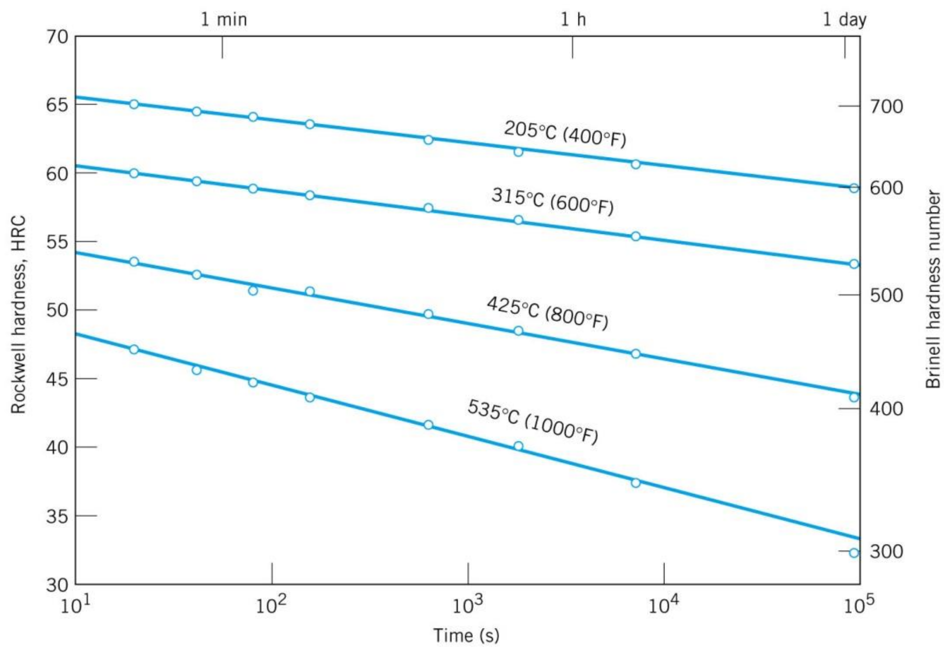
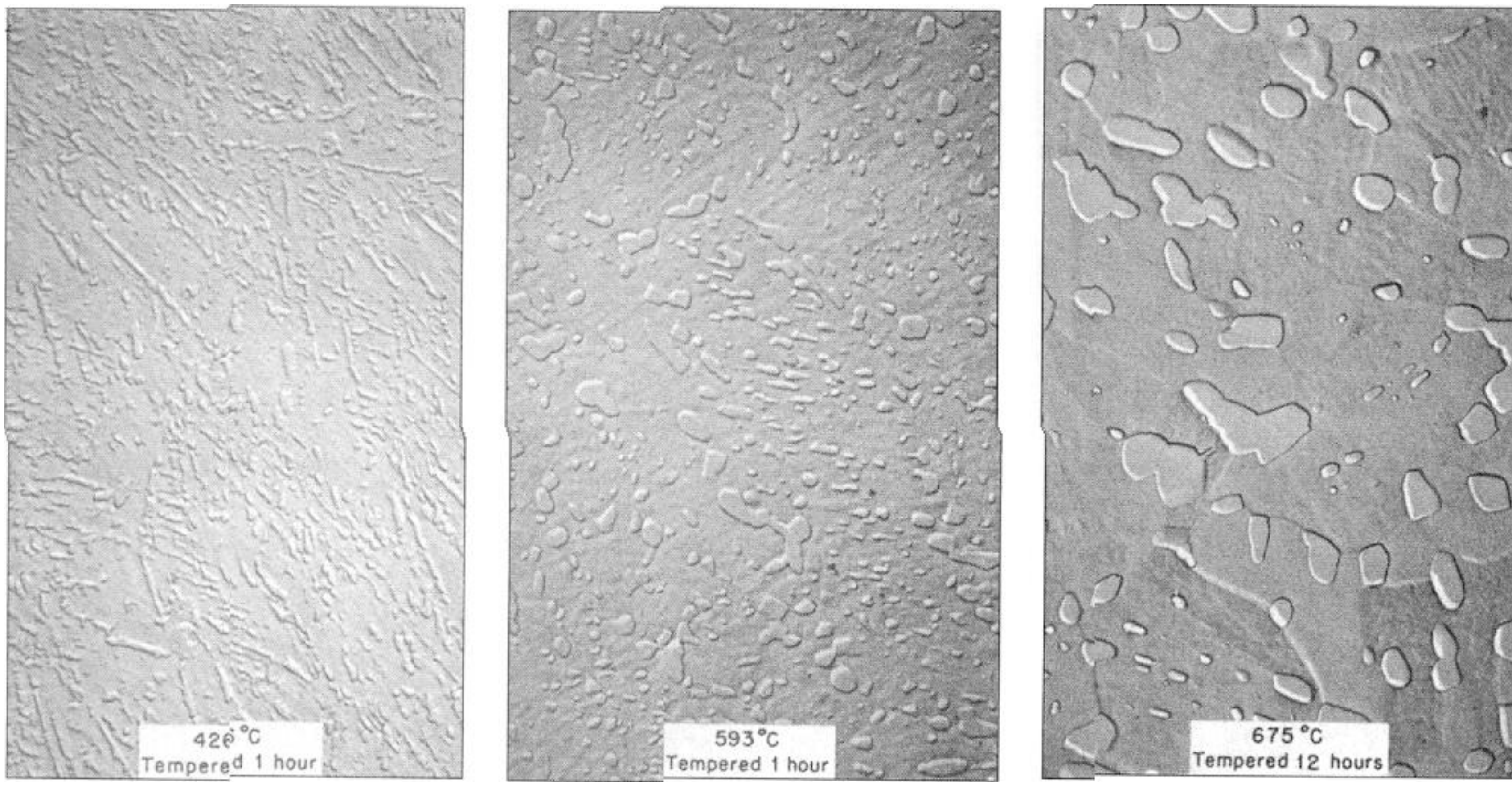


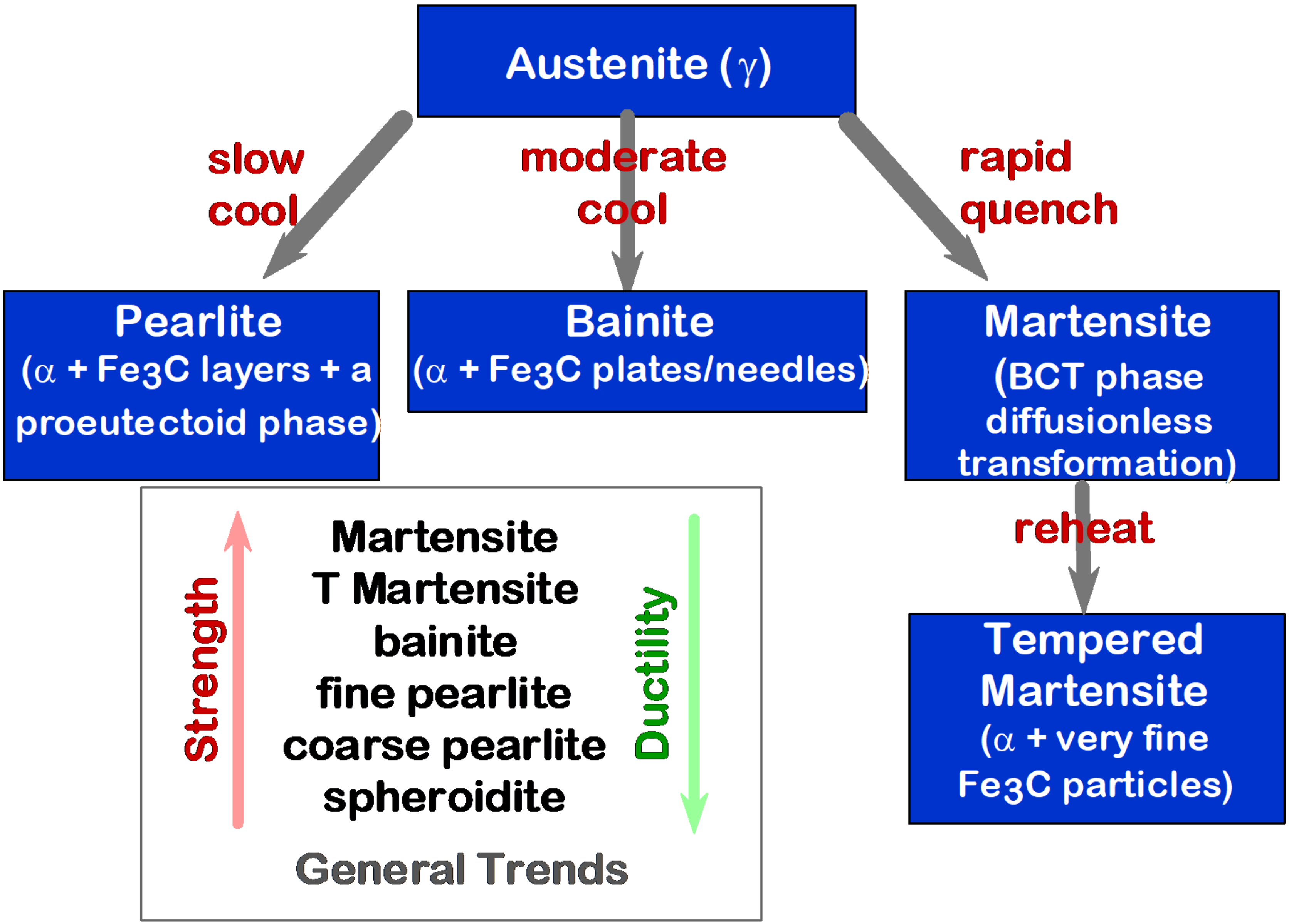
FIGURE 10.26 Hardness versus tempering time for a water-quenched eutectoid plain carbon (1080) steel. (Adapted from Edgar C. Bain, *Functions of the Alloying Elements in Steel,* American Society for Metals, 1939, p. 233.)

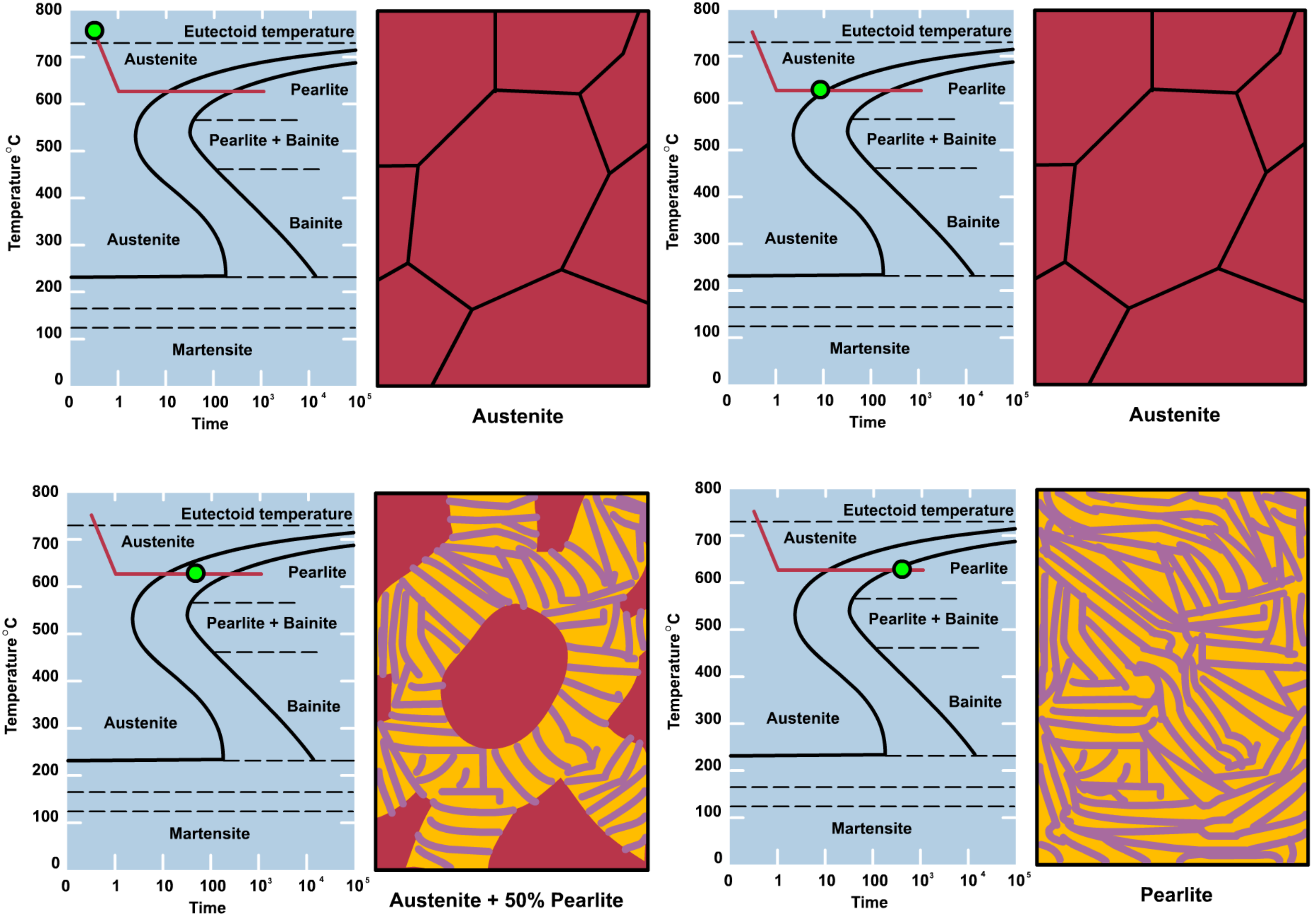
Spheroidite



0.7 wt% C

Summary: Processing Options





800
700
600
500
400
300
200
100
0
Temperature °C
Eutectoid temperature
Austenite
Pearlite
Pearlite + Bainite
Bainite
Austenite
Martensite
0
1
10
100
10³
10⁴
10⁵
Time
Austenite
Eutectoid temperature
Austenite
Pearlite
Pearlite + Bainite
Bainite
Austenite
Martensite
Time
Austenite
Eutectoid temperature
Austenite
Pearlite
Pearlite + Bainite
Bainite
Austenite
Martensite
Time
Austenite + 50% Pearlite
Eutectoid temperature
Austenite
Pearlite
Pearlite + Bainite
Bainite
Austenite
Martensite
Time
Pearlite