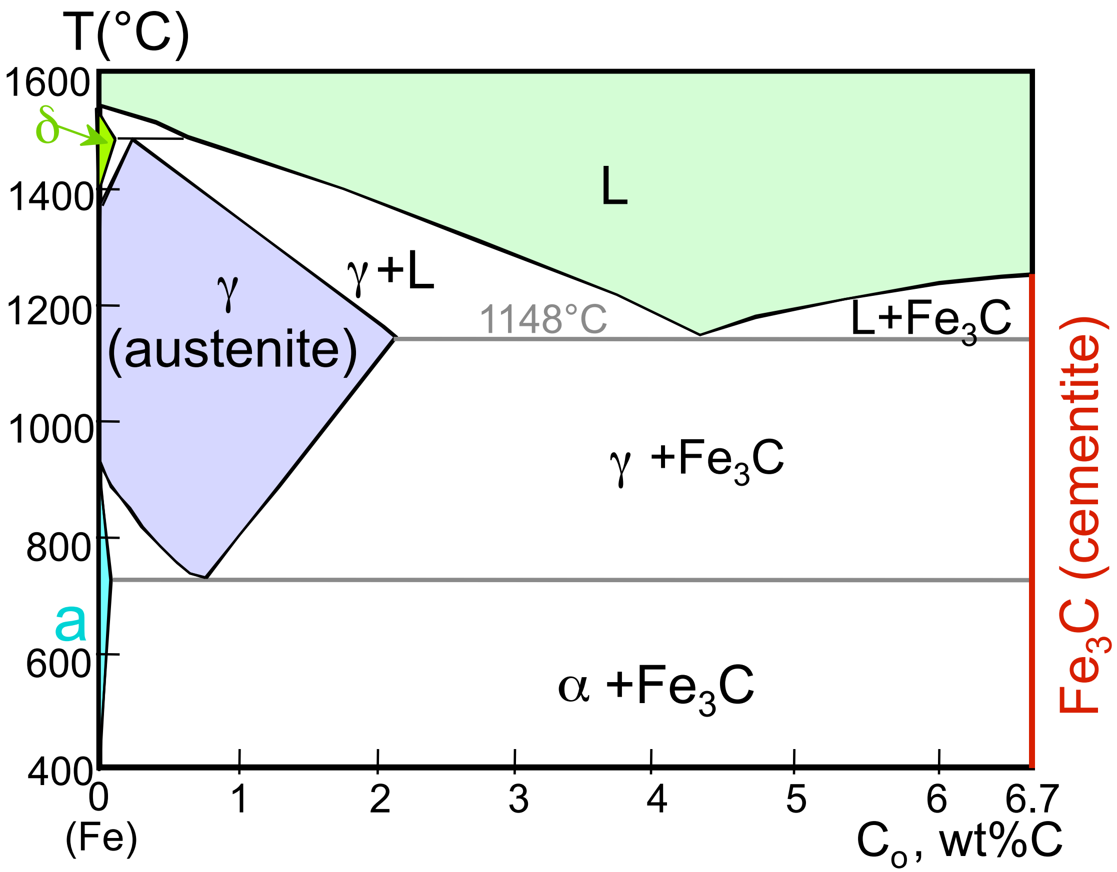
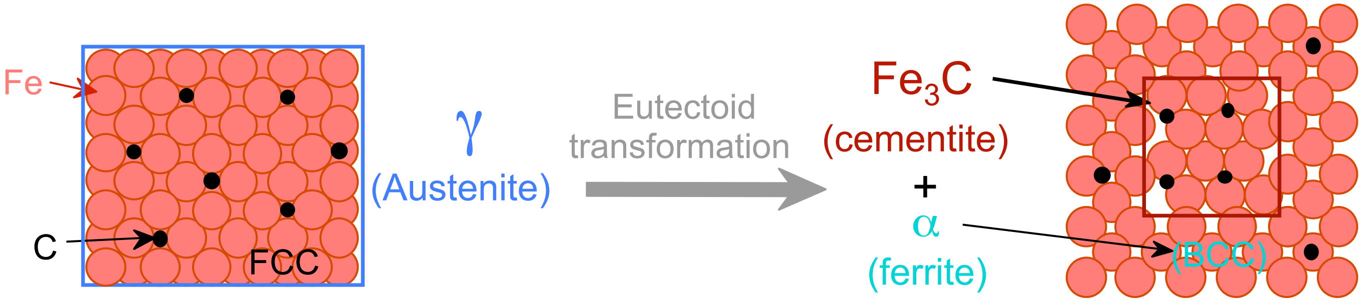
Chapter 10:
Phase Transformations



Chapter 10:
Phase Transformations

- Transforming one phase into another takes time.



- How does the rate of transformation depend on time and *T*?
- How can we slow down the transformation so that we can engineer non-equilibrium structures?
- Are the mechanical properties of non-equilibrium structures better?

t=time!

T=temperature!

ΔT= temperature difference from phase transition temperature

Phase Transformations

Nucleation

- nuclei (seeds) act as template to grow crystals

Driving force to nucleate increases as we increase ΔT

In Δ T range close to T_m, rate of nucleation higher with higher Δ T

- supercooling (eutectic, eutectoid)

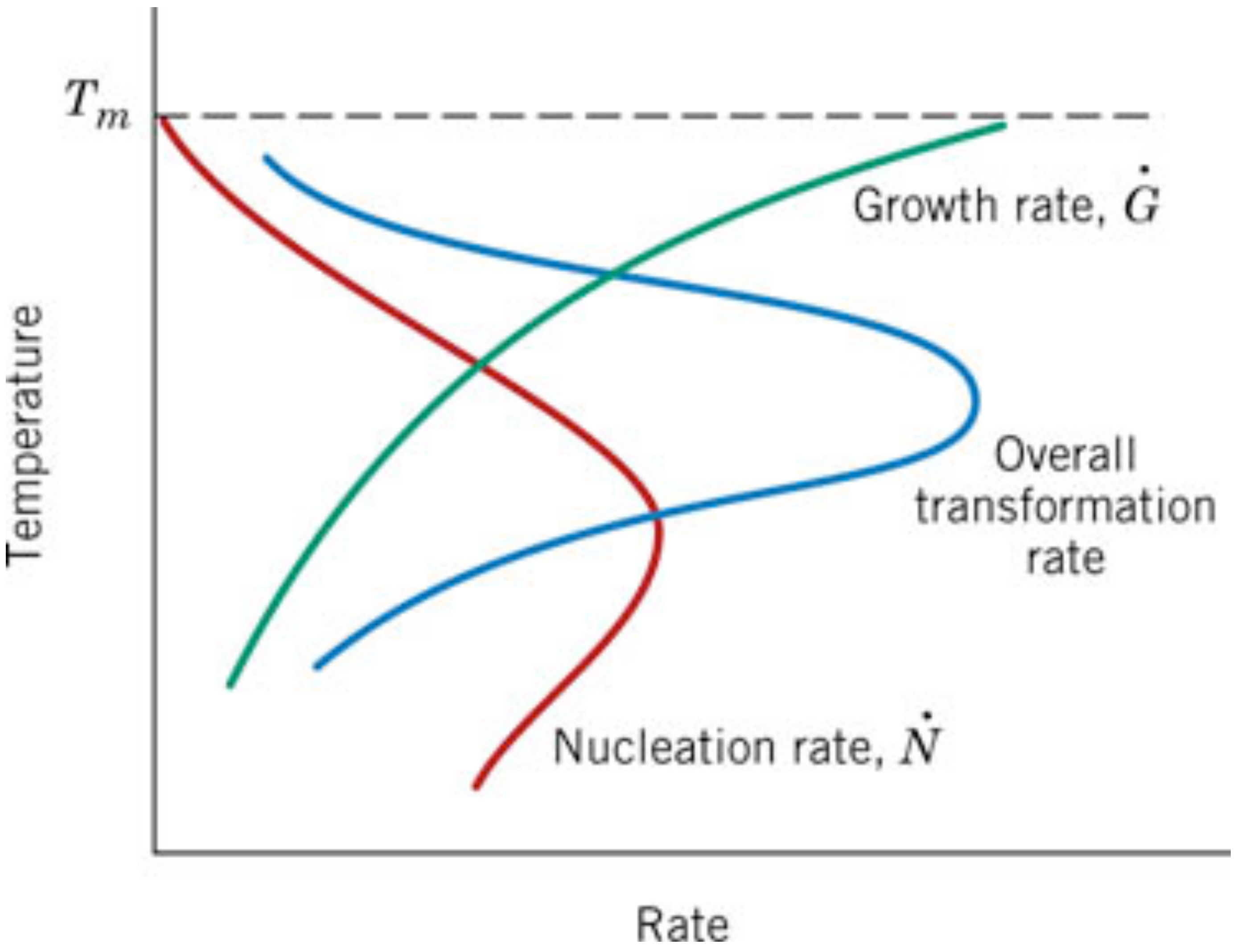
Growth

Growth rate increases with T (thermally activated)

$$dG/dt = C \exp(-Q/kT)$$

Small supercooling → few nuclei - large crystals

Large supercooling → rapid nucleation - many nuclei, small crystals

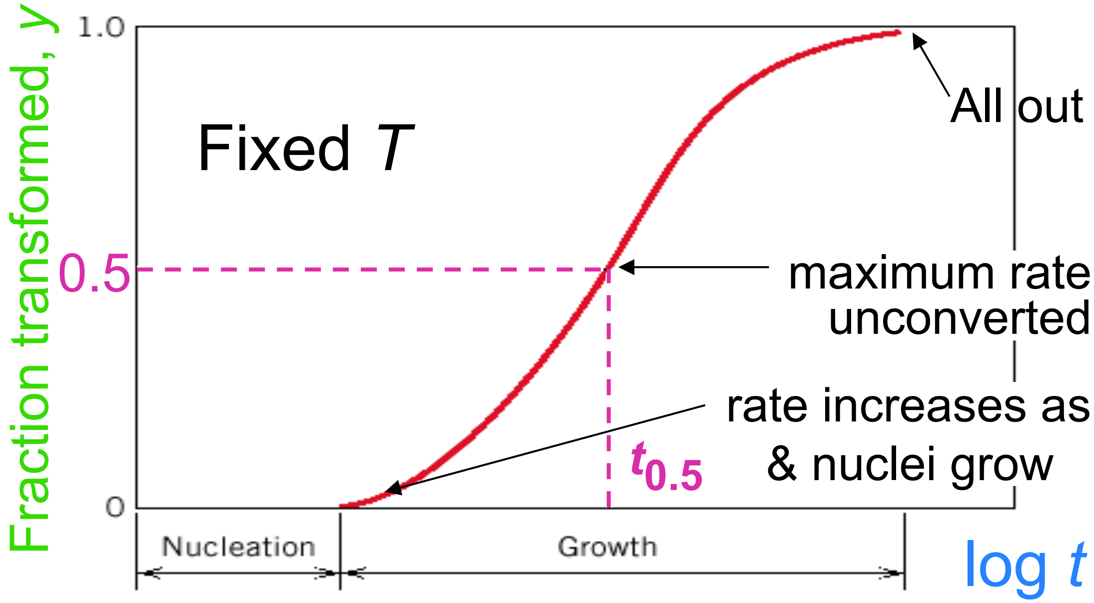

T_m
Growth rate, $\dot{G}$
Overall transformation rate
Nucleation rate, $\dot{N}$
Temperature
Rate

Rate of Phase Transformations

Kinetics - measure approach to equilibrium vs. time

- Hold temperature constant & measure conversion vs. time
  - How is conversion measured?
    - X-ray diffraction – have to do many samples
    - electrical conductivity – follow one sample
    - sound waves – one sample

Rate of Phase Transformation



All out of material - done

maximum rate reached – now amount unconverted decreases so rate slows

rate increases as surface area increases & nuclei grow

Adapted from Fig. 10.10, *Callister 7e.*

Avrami rate equation => $y = 1 - \exp(-kt^n)$

fraction transformed

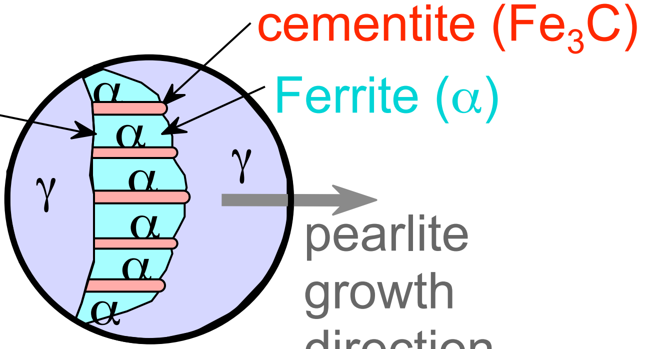
time

- k & n fit for specific sample

By convention $\boxed{r = 1 / t_{0.5}}$

Eutectoid Transformation Rate

- Growth of pearlite from austenite:



Austenite (γ) grain boundary

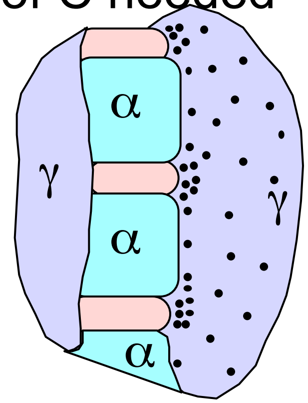
cementite (Fe_3C)

Ferrite (α)

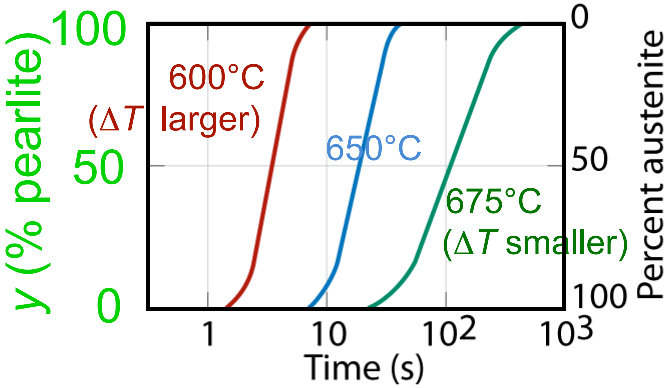
pearlite growth direction

Adapted from Fig. 9.15, *Callister 7e*.

Diffusive flow of C needed



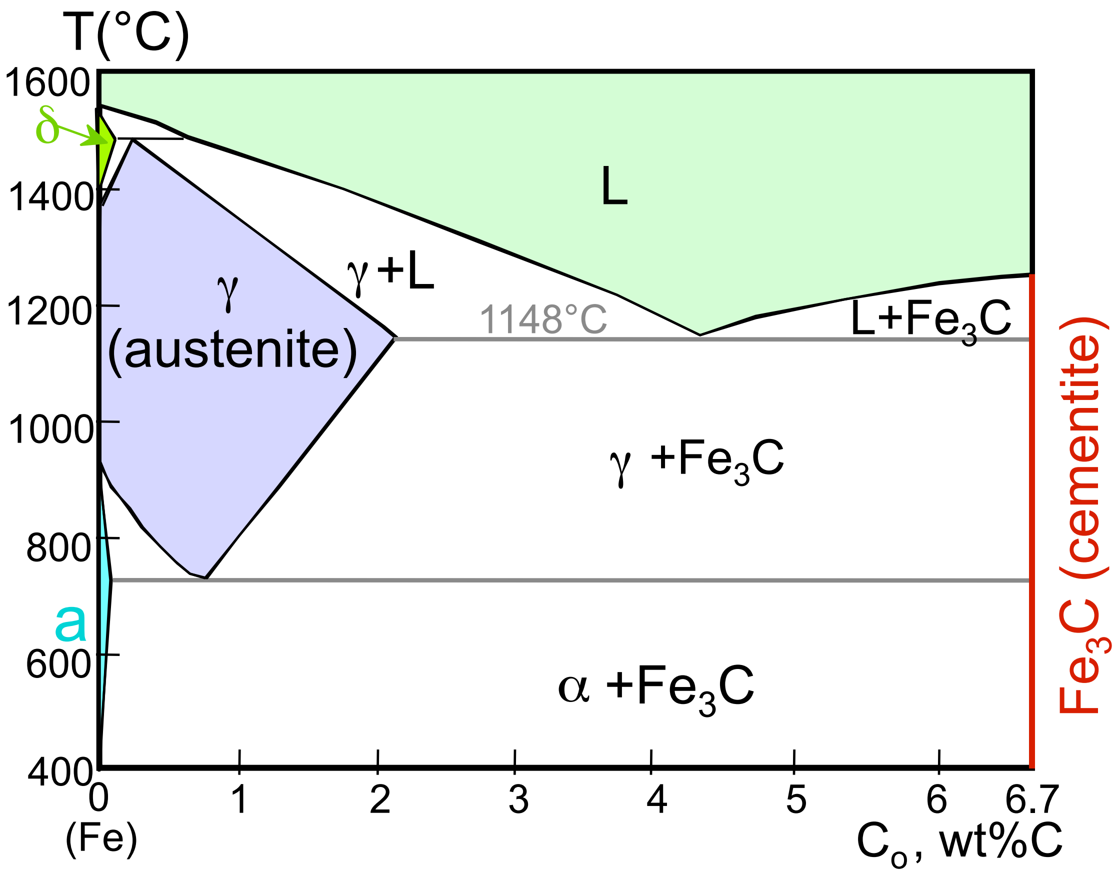
- Recrystallization rate increases with ΔT.



Adapted from Fig. 10.12, *Callister 7e*.

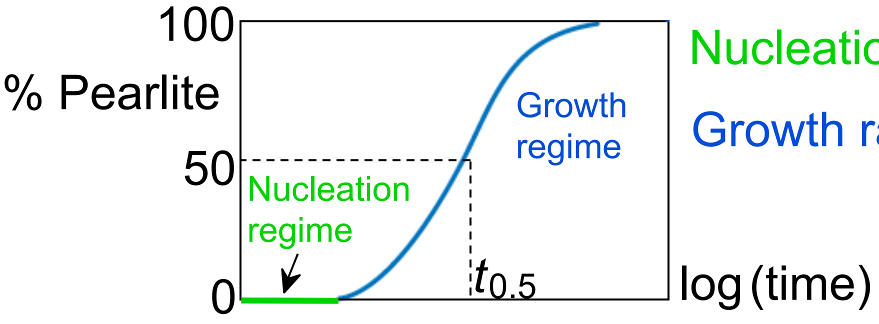
Course pearlite → formed at higher T - softer

Fine pearlite → formed at low T - harder


T(°C)
1600
1400
1200
1000
800
600
400
δ
L
γ+L
γ
(austenite)
1148°C
L+Fe$_3$C
γ +Fe$_3$C
a
α +Fe$_3$C
Fe$_3$C (cementite)
0
(Fe)
1
2
3
4
5
6
6.7
C$_o$, wt%C

Nucleation and Growth

- Reaction rate is a result of nucleation <u>and</u> growth of crystals.

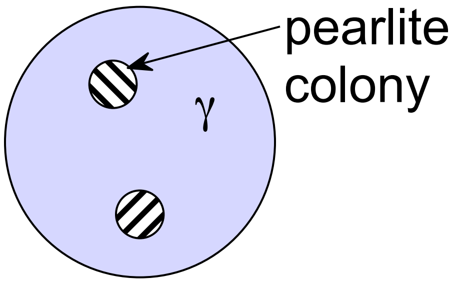


Nucleation rate increases with ΔT

Growth rate increases with T

Adapted from
Fig. 10.10, *Callister 7e*.

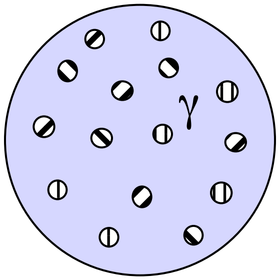
- Examples:



T just below T_E

Nucleation rate low

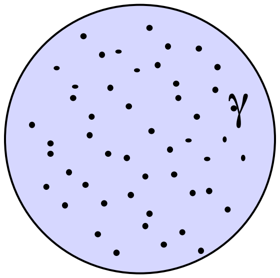
Growth rate high



T moderately below T_E

Nucleation rate med .

Growth rate med.



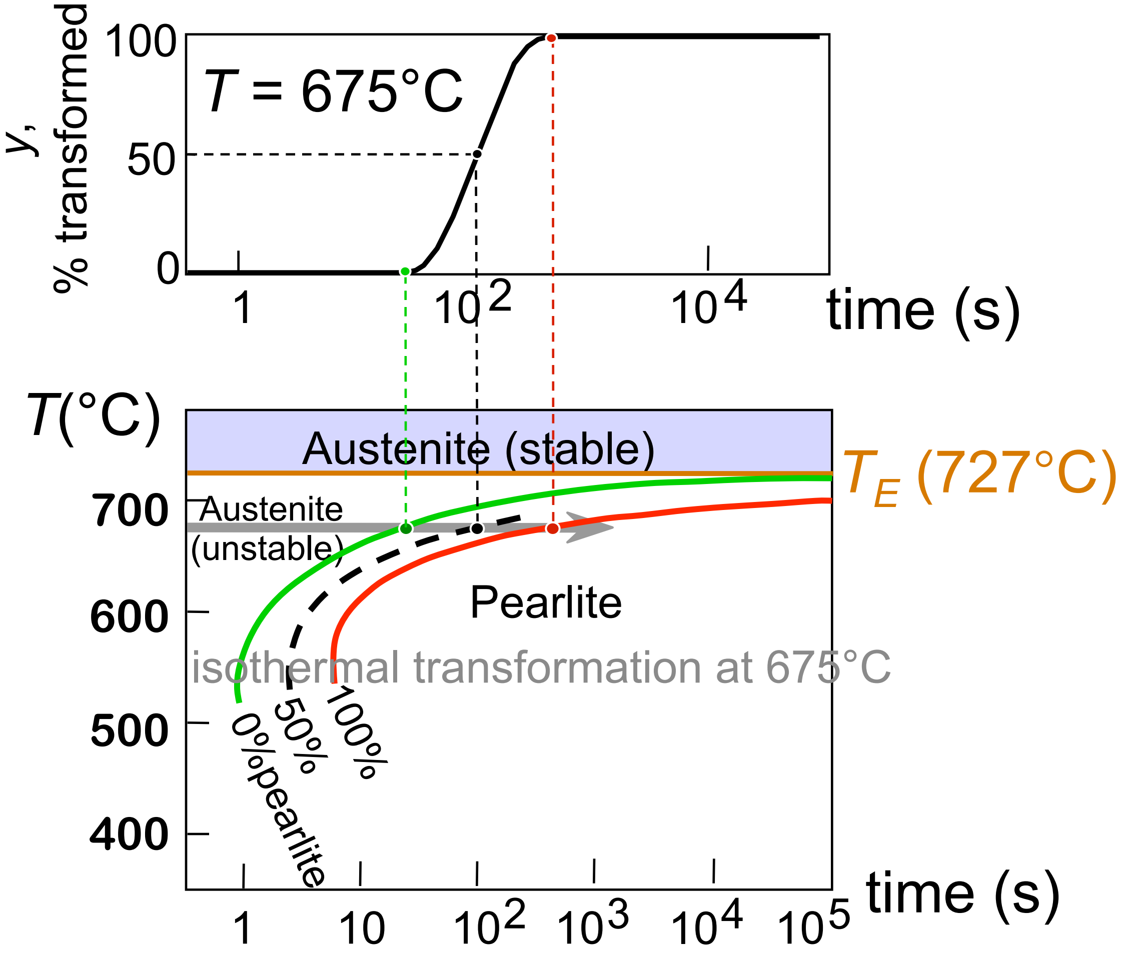
T way below T_E

Nucleation rate high

Growth rate low

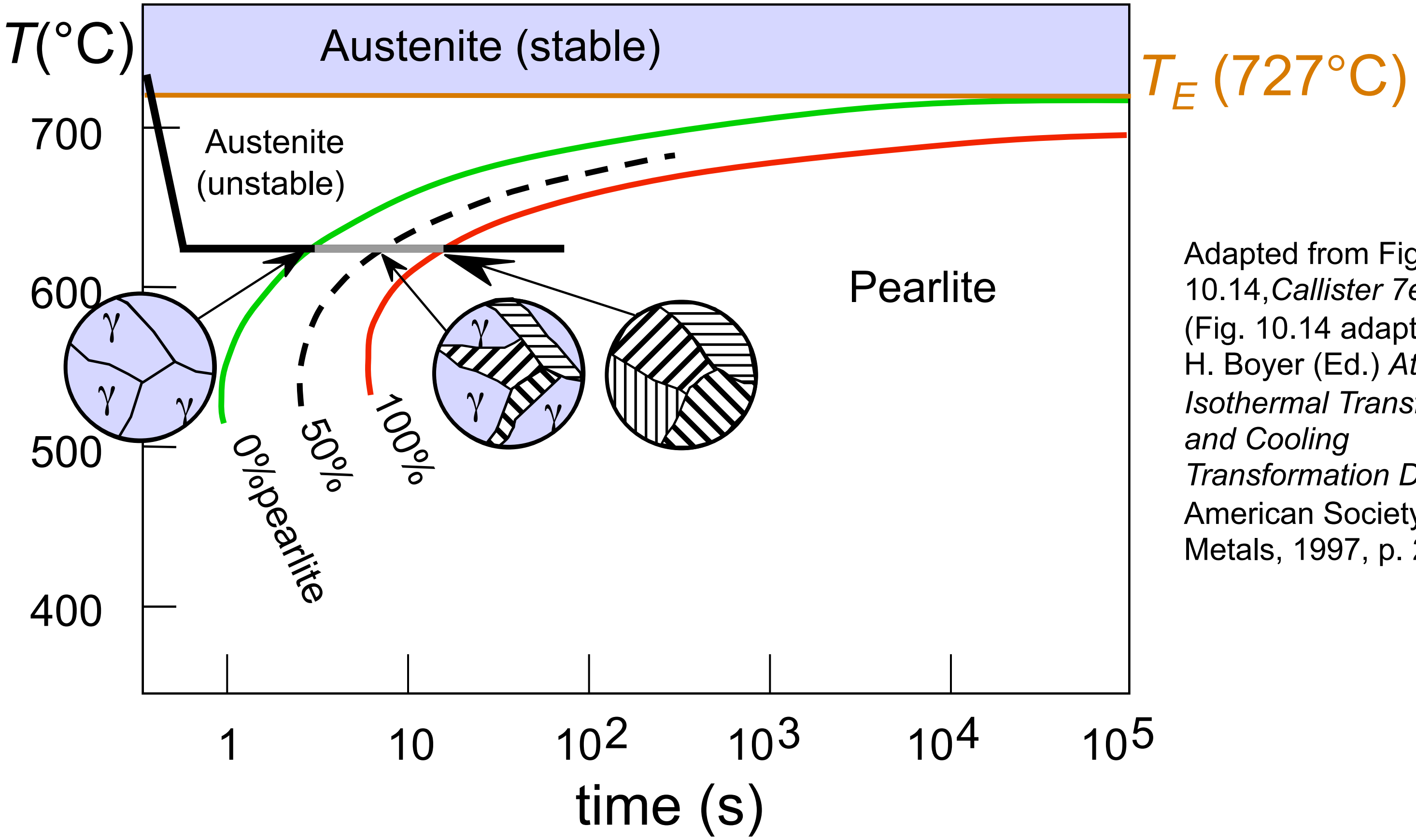
Isothermal Transformation Diagrams

- Fe-C system, C_o = 0.76 wt% C
- Transformation at T = 675°C.



Effect of Cooling History in Fe-C System

- Eutectoid composition, C_o = 0.76 wt% C
- Begin at T > 727°C
- Rapidly cool to 625°C and hold isothermally.



Adapted from Fig. 10.14,*Callister 7e*.
(Fig. 10.14 adapted from H. Boyer (Ed.) *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, 1997, p. 28.)

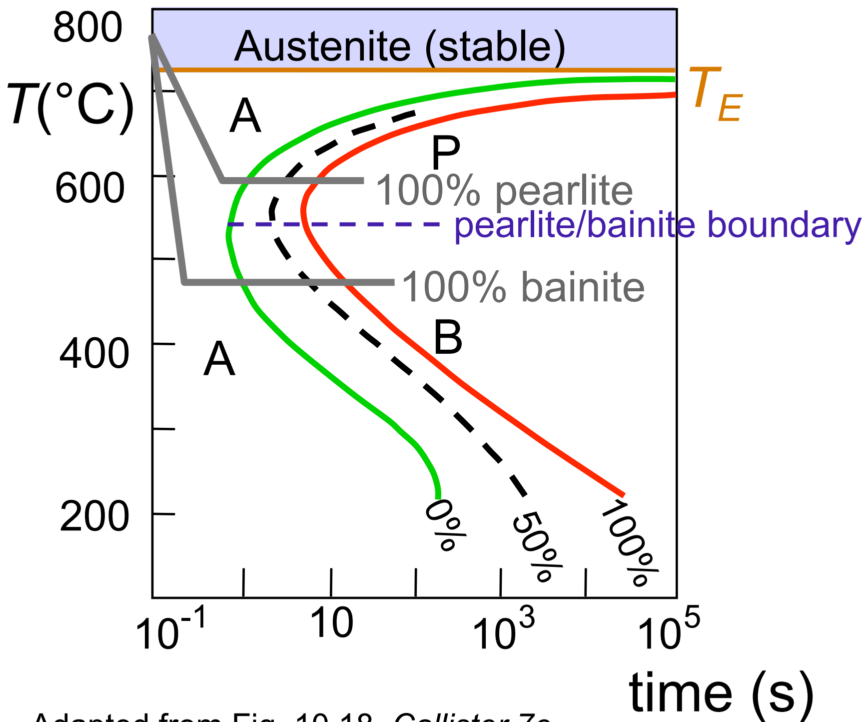
Non-Equilibrium Transformation Products: Fe-C

- Bainite:

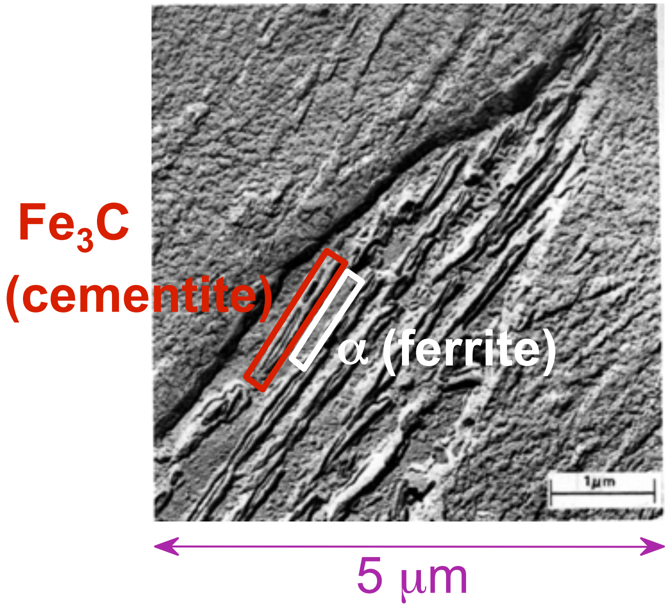
  --α lathes (strips) with long rods of Fe_3C

  --diffusion controlled.

- Isothermal Transf. Diagram



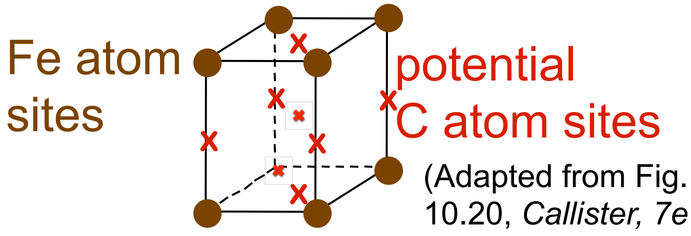
Adapted from Fig. 10.18, *Callister 7e*.
(Fig. 10.18 adapted from H. Boyer (Ed.) *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, 1997, p. 28.)



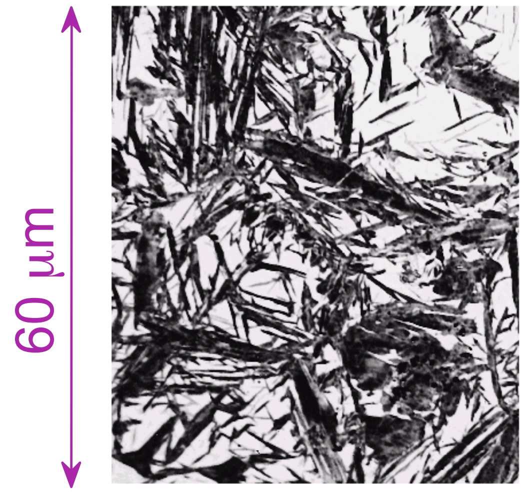
(Adapted from Fig. 10.17, *Callister, 7e*. (Fig. 10.17 from *Metals Handbook*, 8th ed., Vol. 8, *Metallography, Structures, and Phase Diagrams*, American Society for Metals, Materials Park, OH, 1973.)

Martensite: Fe-C System

- Martensite:
  --γ(FCC) to Martensite (BCT)
  (involves single atom jumps)



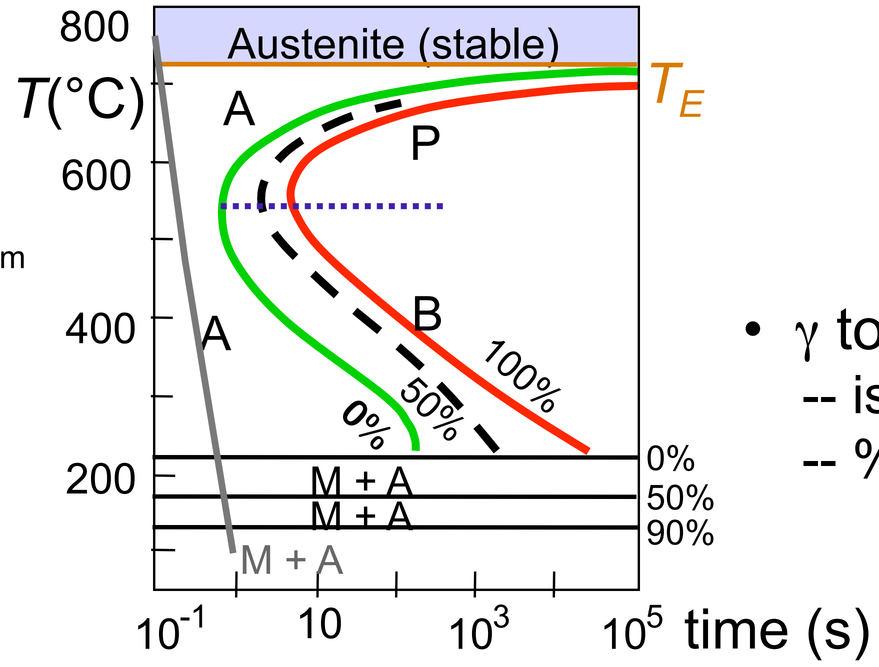
(Adapted from Fig. 10.20, *Callister, 7e*.



▬ Martensite needles
▬ Austenite

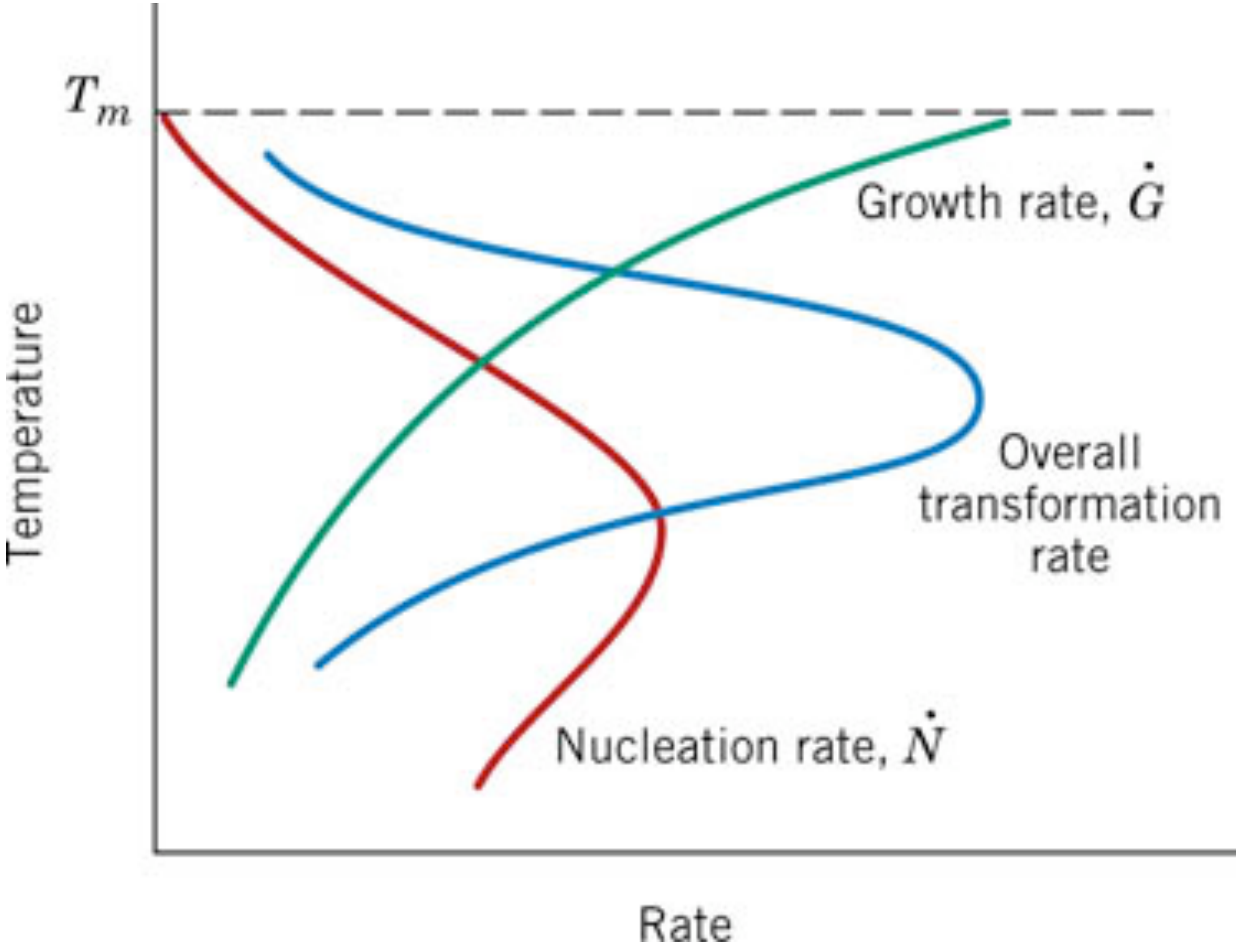
(Adapted from Fig. 10.21, *Callister, 7e*. (Fig. 10.21 courtesy United States Steel Corporation.)

- Isothermal Transf. Diagram

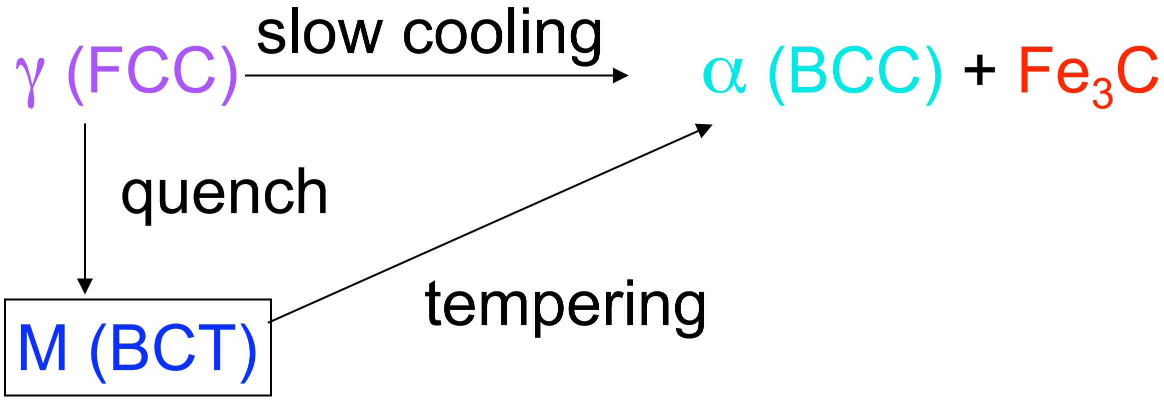


Adapted from Fig. 10.22, *Callister 7e*.

- γ to M transformation..
  -- is rapid!
  -- % transf. depends on T only.


T_m
Growth rate, $\dot{G}$
Overall transformation rate
Nucleation rate, $\dot{N}$
Temperature
Rate

Martensite Formation



γ (FCC)

slow cooling

α (BCC) + Fe_3C

quench

M (BCT)

tempering

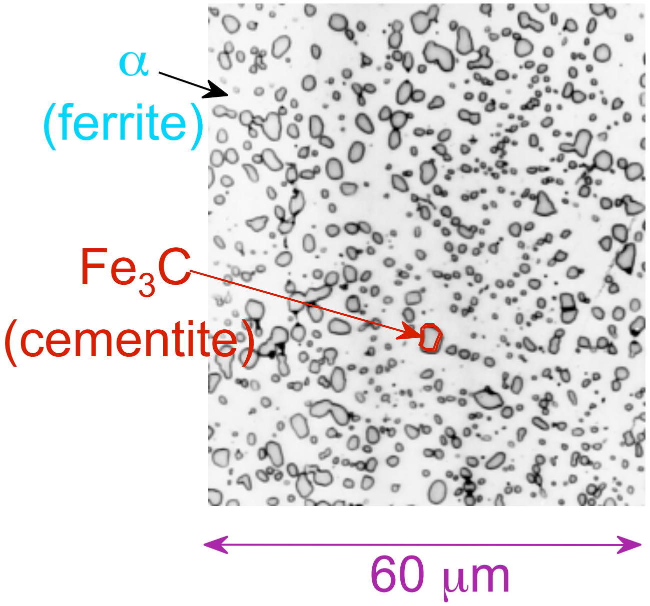
M = martensite is body centered tetragonal (BCT)

Diffusionless transformation BCT if $C > 0.15$ wt%

BCT → few slip planes → hard, brittle

Spheroidite: Fe-C System

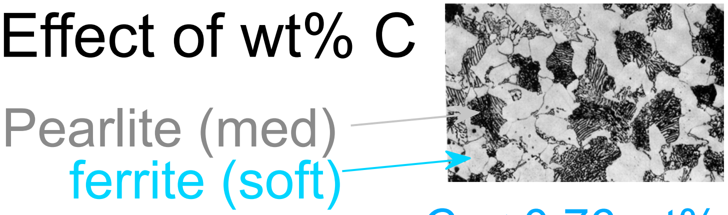
- Spheroidite:
  --α grains with spherical Fe_3C
  --diffusion dependent.
  --heat bainite or pearlite for long times
  --reduces interfacial area (driving force)



(Adapted from Fig. 10.19, *Callister, 7e*. (Fig. 10.19 copyright United States Steel Corporation, 1971.)

Mechanical Prop: Fe-C System (1)

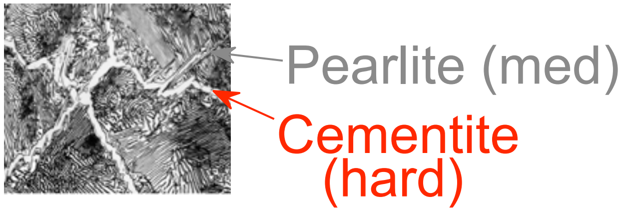
- Effect of wt% C



Adapted from Fig. 9.30, *Callister 7e*. (Fig. 9.30 courtesy Republic Steel Corporation.)

$C_o < 0.76$ wt% C

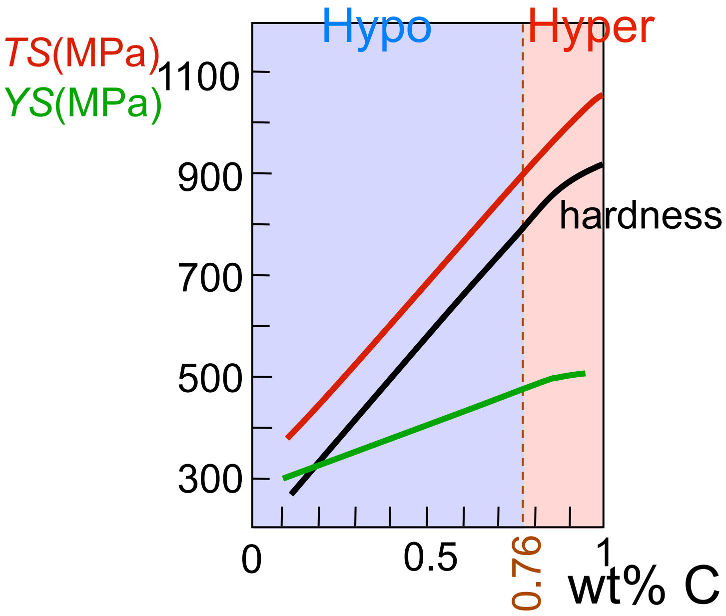
Hypoeutectoid

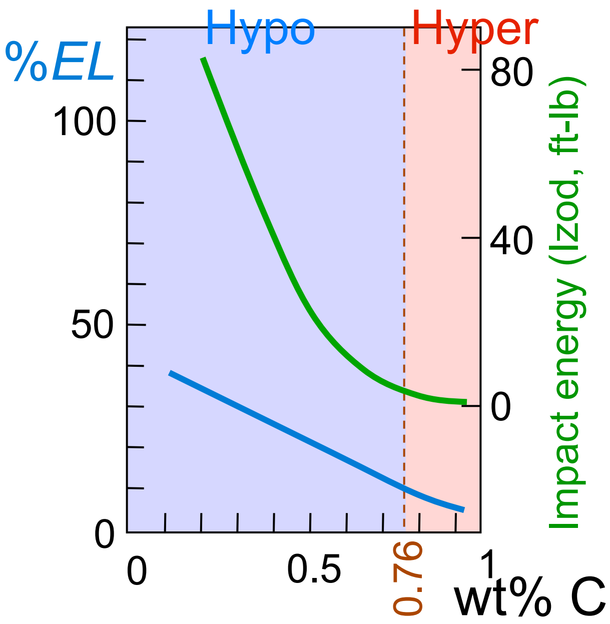


$C_o > 0.76$ wt% C

Hypereutectoid

Adapted from Fig. 9.33, *Callister 7e*. (Fig. 9.33 copyright 1971 by United States Steel Corporation.)



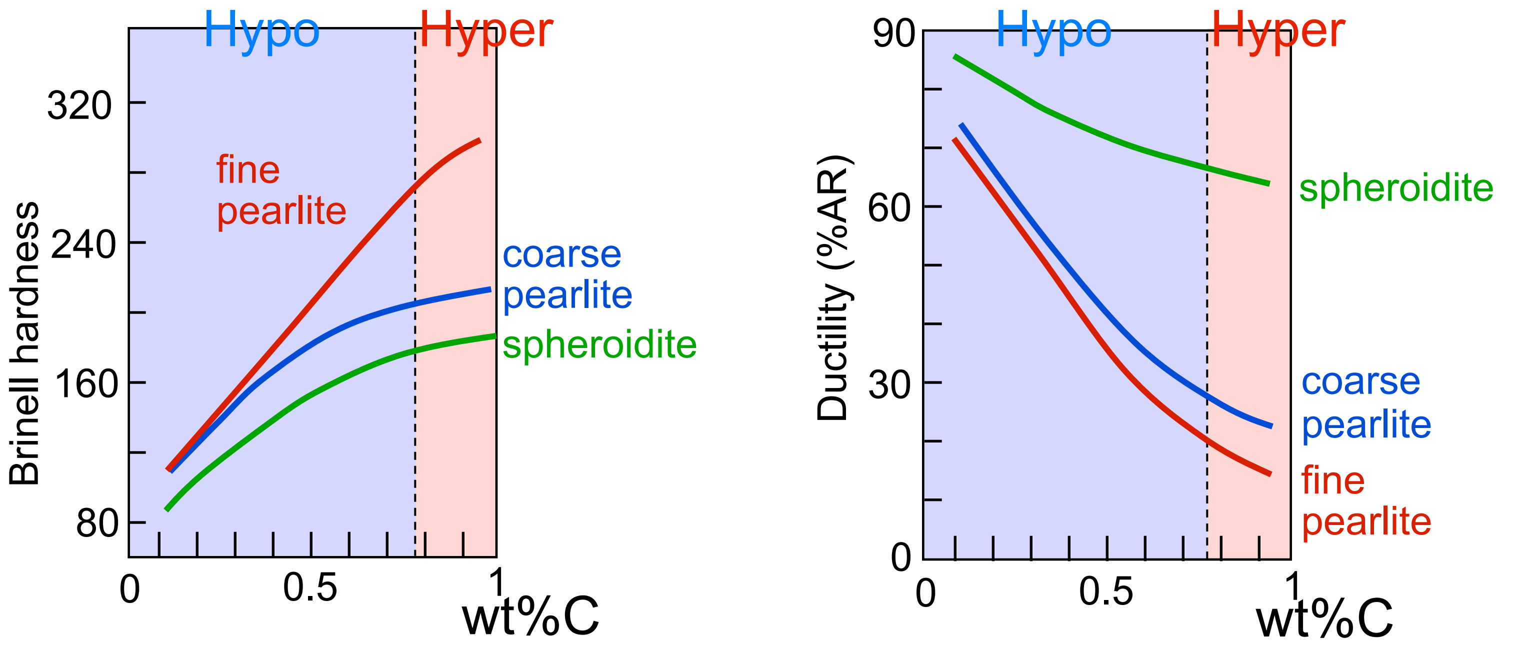


Adapted from Fig. 10.29, *Callister 7e*. (Fig. 10.29 based on data from *Metals Handbook: Heat Treating*, Vol. 4, 9th ed., V. Masseria (Managing Ed.), American Society for Metals, 1981, p. 9.)

- More wt% C: *TS* and *YS* increase, %*EL* decreases.

Mechanical Prop: Fe-C System (2)

- Fine vs coarse pearlite vs spheroidite

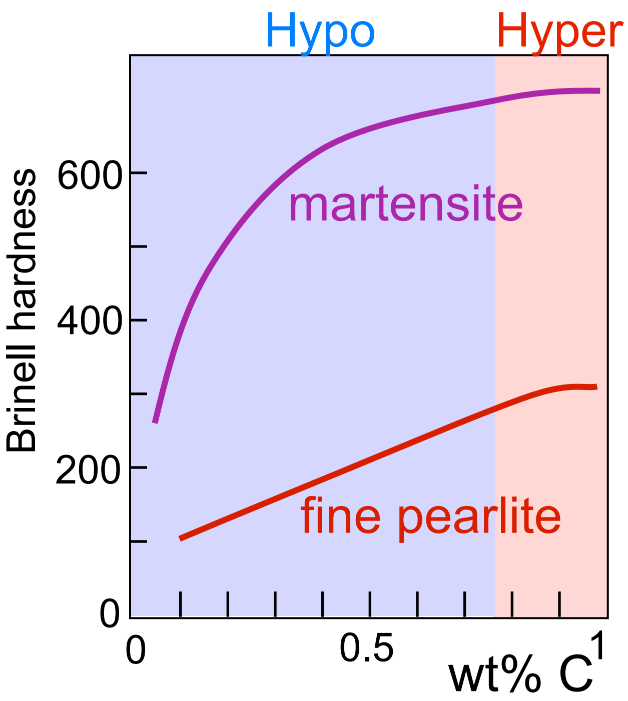


- Hardness: fine > coarse > spheroidite
- %RA: fine < coarse < spheroidite

Adapted from Fig. 10.30, *Callister 7e*. (Fig. 10.30 based on data from *Metals Handbook: Heat Treating*, Vol. 4, 9th ed., V. Masseria (Managing Ed.), American Society for Metals, 1981, pp. 9 and 17.)

Mechanical Prop: Fe-C System (3)

- Fine Pearlite vs Martensite:

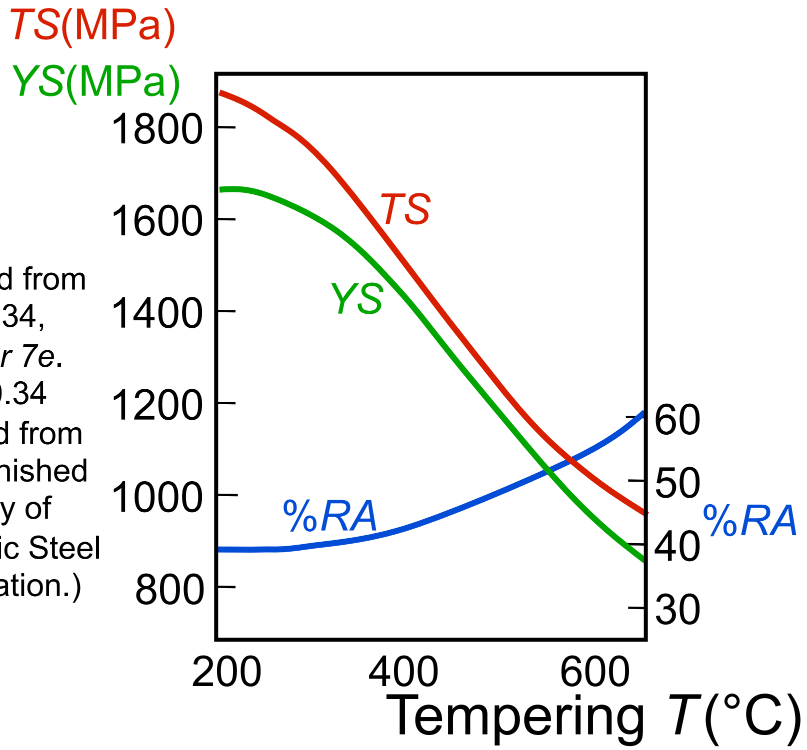


Adapted from Fig. 10.32, *Callister 7e*. (Fig. 10.32 adapted from Edgar C. Bain, *Functions of the Alloying Elements in Steel*, American Society for Metals, 1939, p. 36; and R.A. Grange, C.R. Hribal, and L.F. Porter, *Metall. Trans. A*, Vol. 8A, p. 1776.)

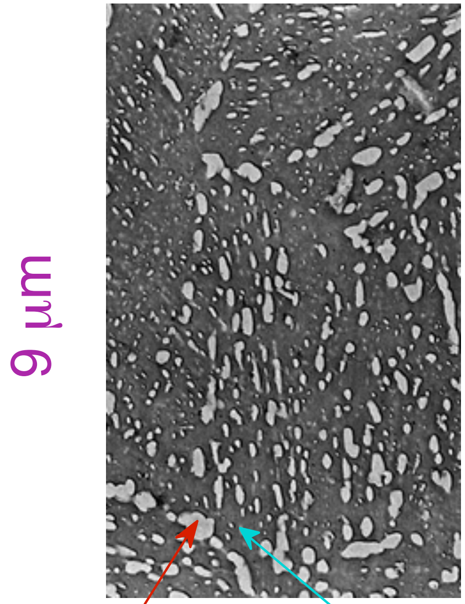
- Hardness: fine pearlite << martensite.

Tempering Martensite

- reduces brittleness of martensite,
- reduces internal stress caused by quenching.



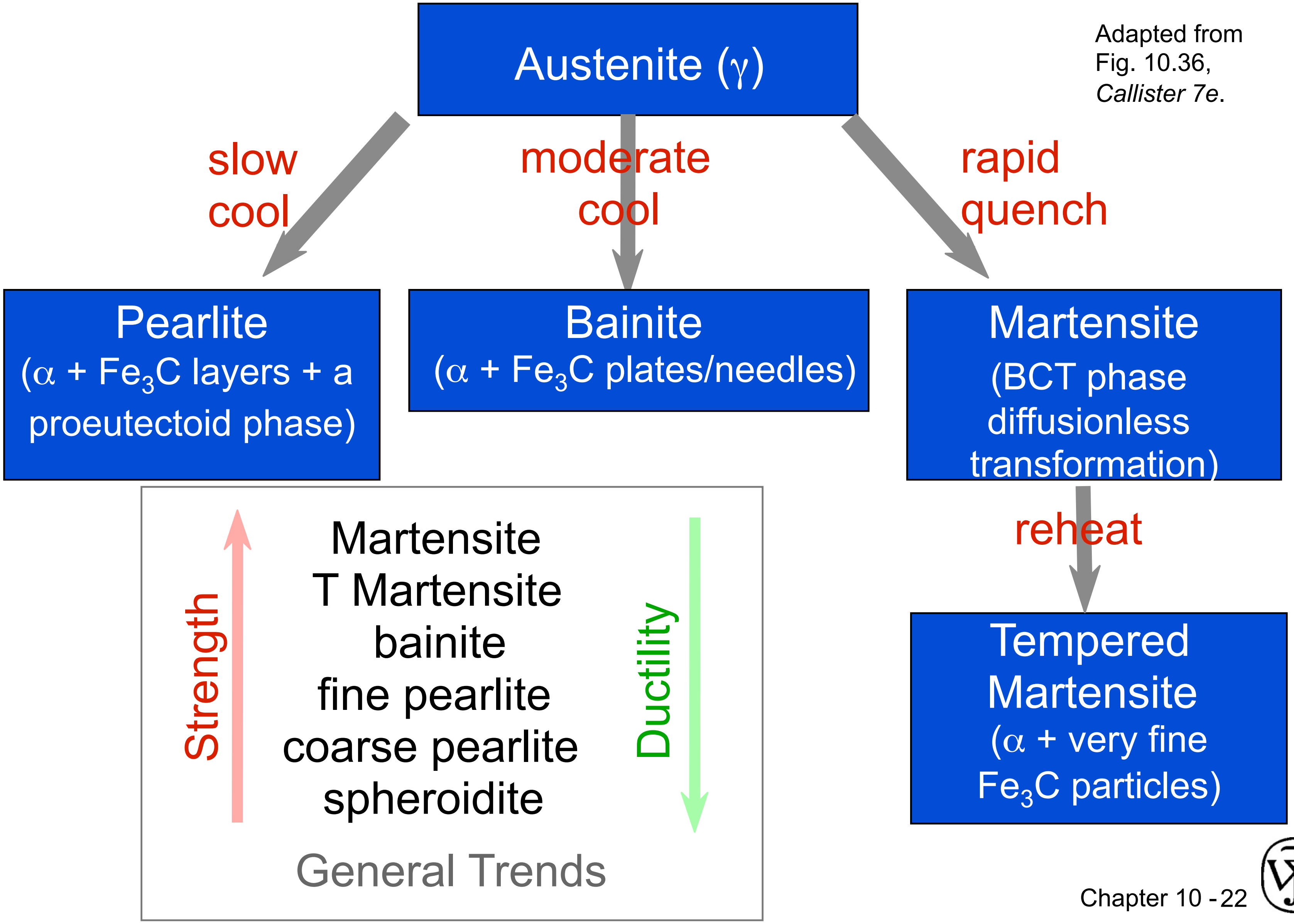
Adapted from Fig. 10.34, *Callister 7e*. (Fig. 10.34 adapted from Fig. furnished courtesy of Republic Steel Corporation.)



Adapted from Fig. 10.33, *Callister 7e*. (Fig. 10.33 copyright by United States Steel Corporation, 1971.)

- produces extremely small Fe_3C particles surrounded by α.
- decreases *TS*, *YS* but increases %*RA*

Summary: Processing Options



Austenite (γ)

slow cool

moderate cool

rapid quench

Adapted from Fig. 10.36, *Callister 7e*.

Pearlite
(α + Fe_3C layers + a proeutectoid phase)

Bainite
(α + Fe_3C plates/needles)

Martensite
(BCT phase diffusionless transformation)

reheat

Tempered Martensite
(α + very fine Fe_3C particles)

Strength

Martensite
T Martensite
bainite
fine pearlite
coarse pearlite
spheroidite

Ductility

General Trends