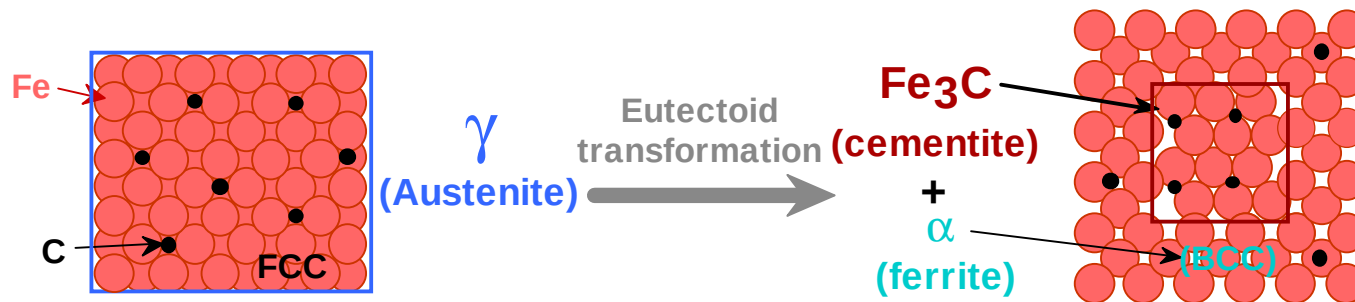


CHAPTER 10:

PHASE TRANSFORMATIONS

ISSUES TO ADDRESS...

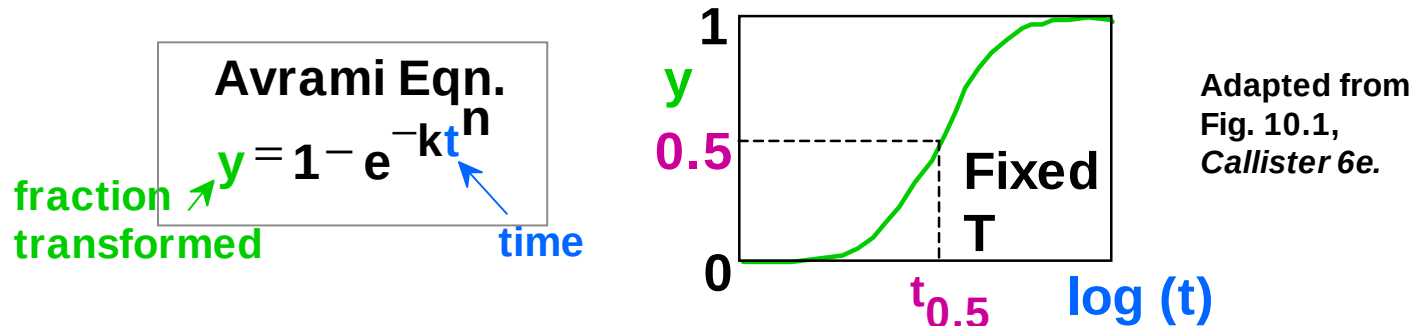
- Transforming one phase into another takes time.



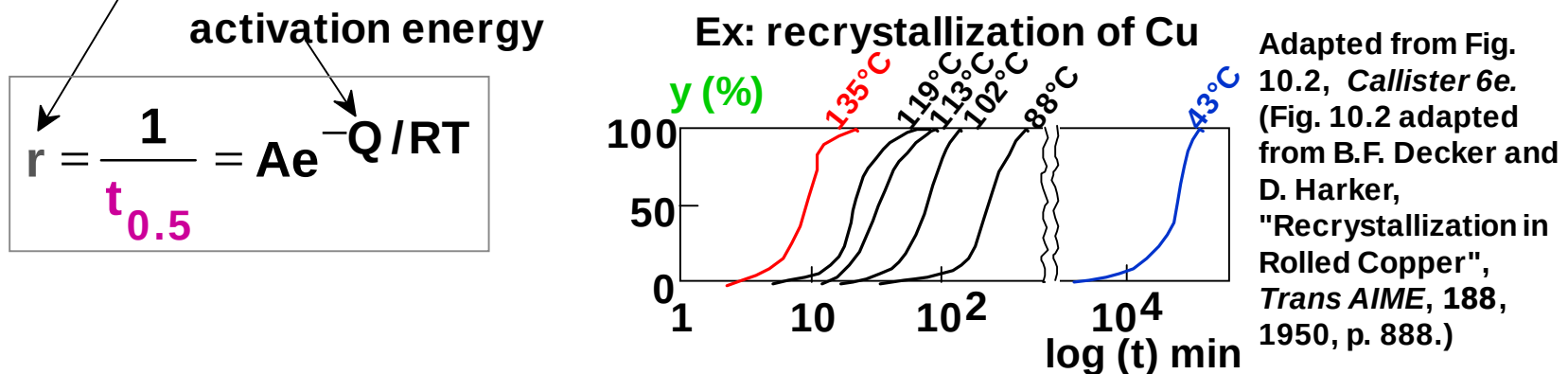
- How does the rate of transformation depend on time and T?
- How can we slow down the transformation so that we can engineering non-equilibrium structures?
- Are the mechanical properties of non-equilibrium structures better?

FRACTION OF TRANSFORMATION

- **Fraction transformed** depends on time.



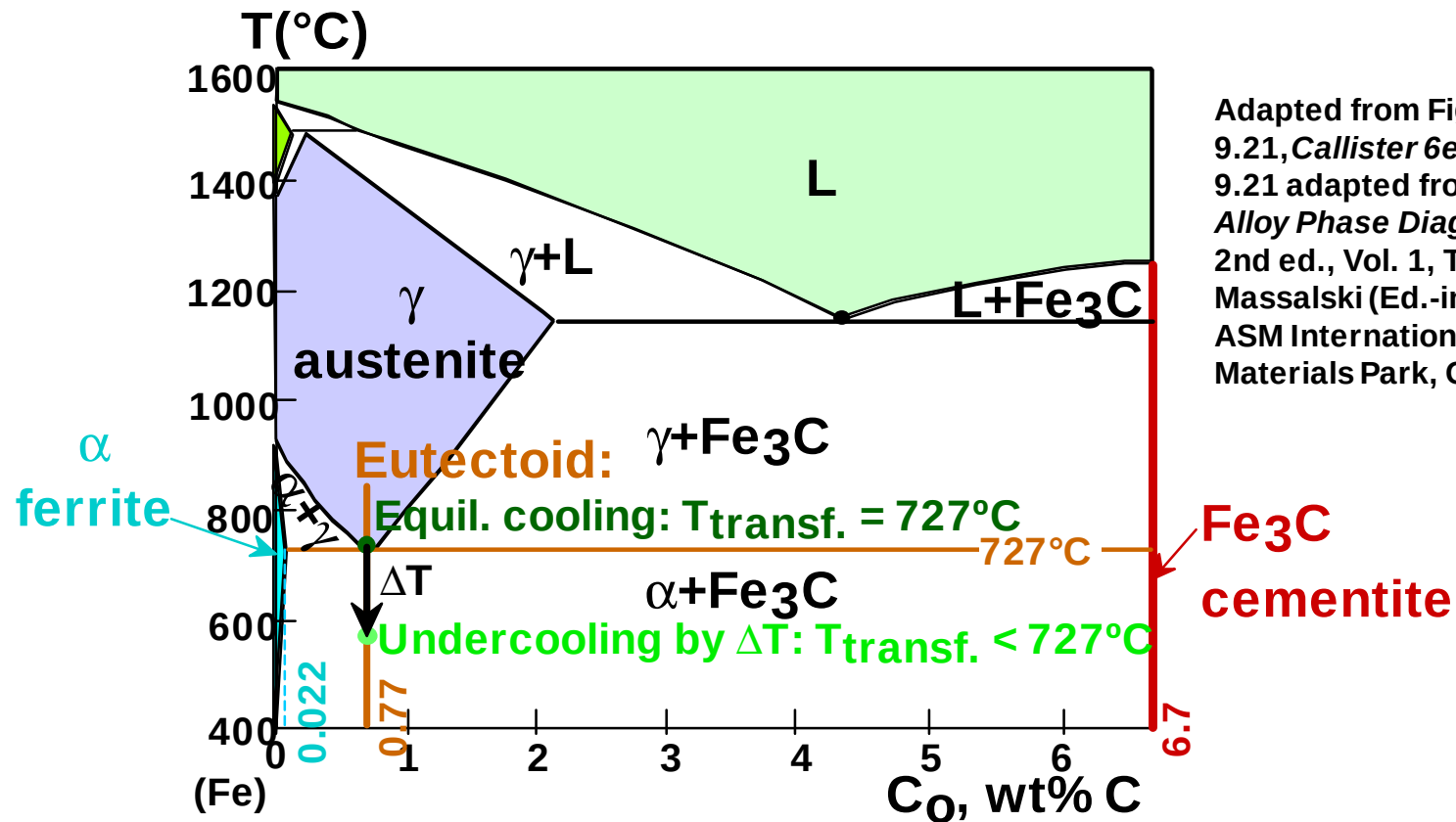
- Transformation rate depends on T.



- **r** often small: equil not possible!

TRANSFORMATIONS & UNDERCOOLING

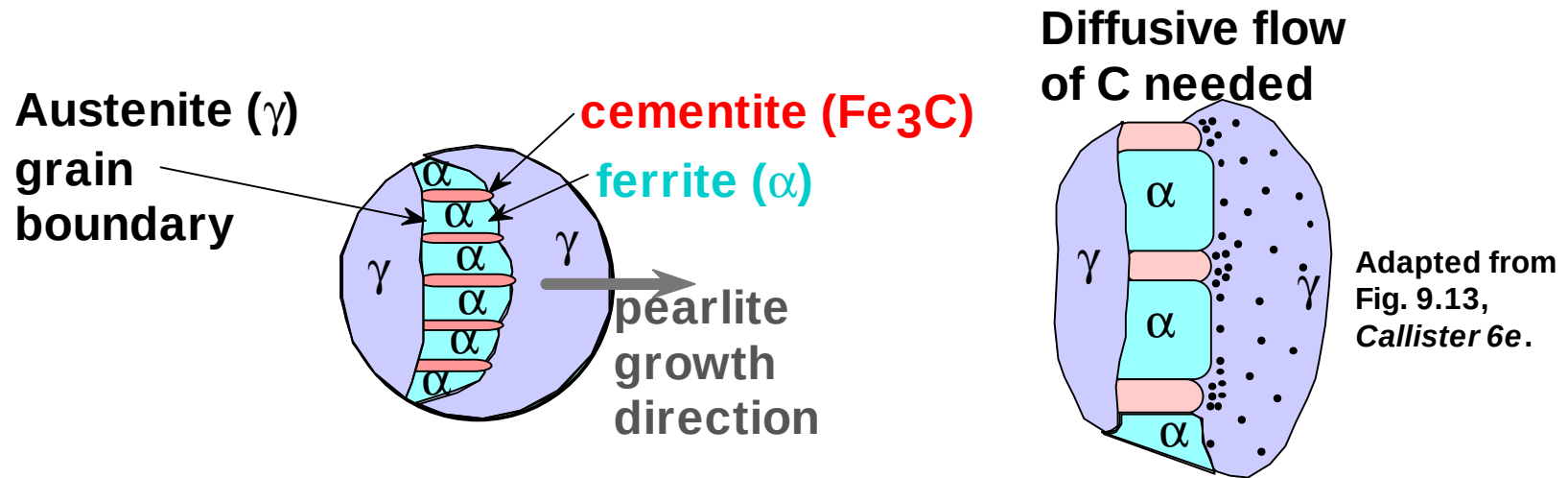
- **Eutectoid** transf. (Fe-C System): $\gamma \Rightarrow \alpha + \text{Fe}_3\text{C}$
- Can make it occur at:
 - ...727°C (cool it slowly)
 - ...below 727°C (“undercool” it!)



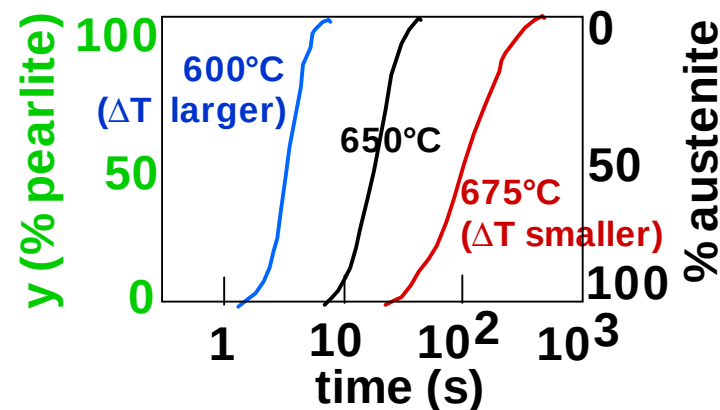
Adapted from Fig. 9.21, Callister 6e. (Fig. 9.21 adapted from *Binary Alloy Phase Diagrams*, 2nd ed., Vol. 1, T.B. Massalski (Ed.-in-Chief), ASM International, Materials Park, OH, 1990.)

EUTECTOID TRANSFORMATION RATE $\sim \Delta T$

- Growth of pearlite from austenite:



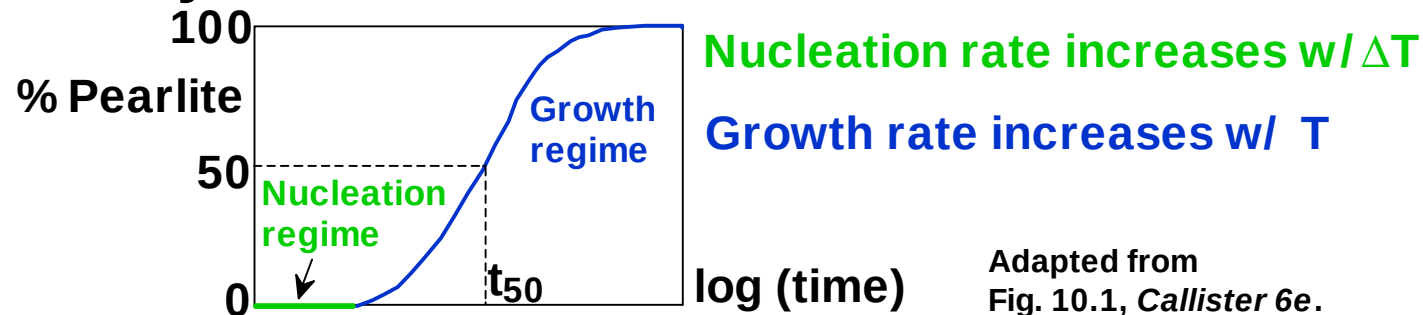
- Reaction rate increases with ΔT .



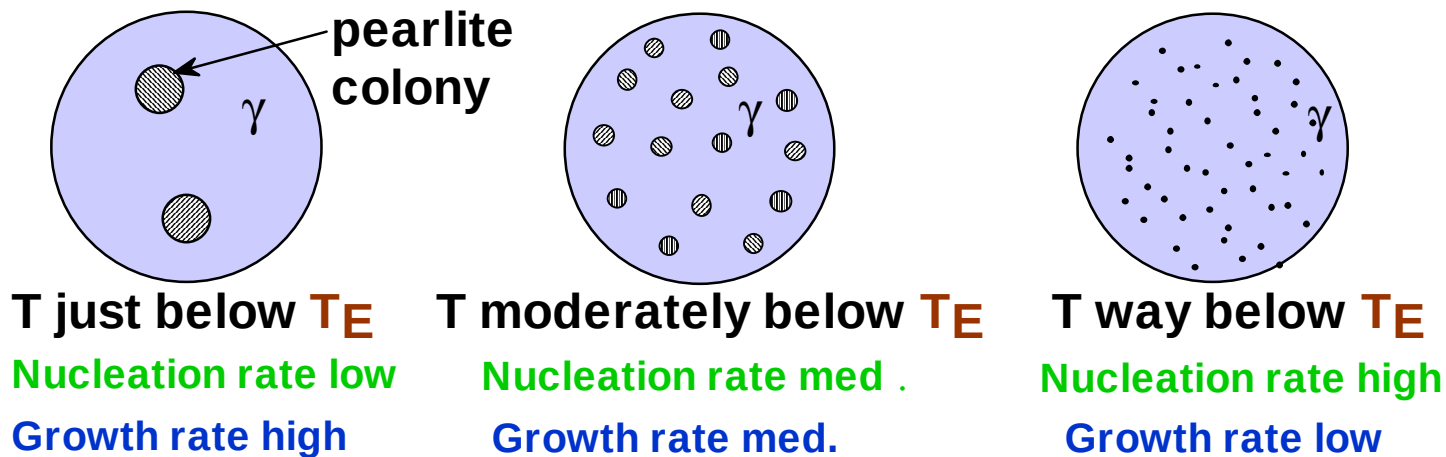
Adapted from Fig. 10.3, Callister 6e.

NUCLEATION AND GROWTH

- Reaction rate is a result of nucleation and growth of crystals.

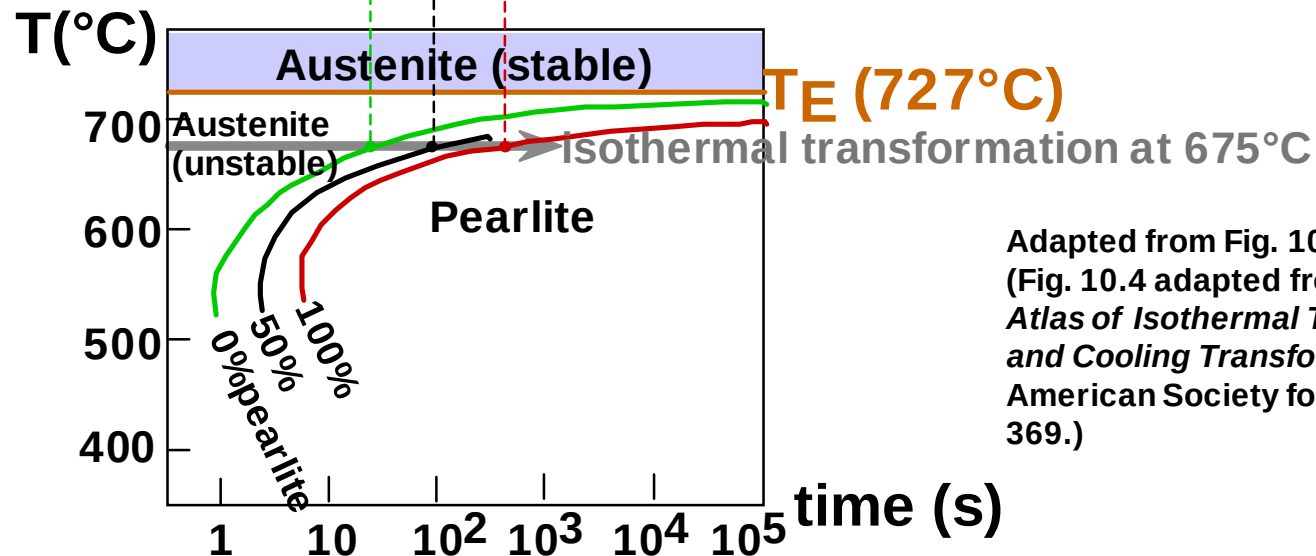
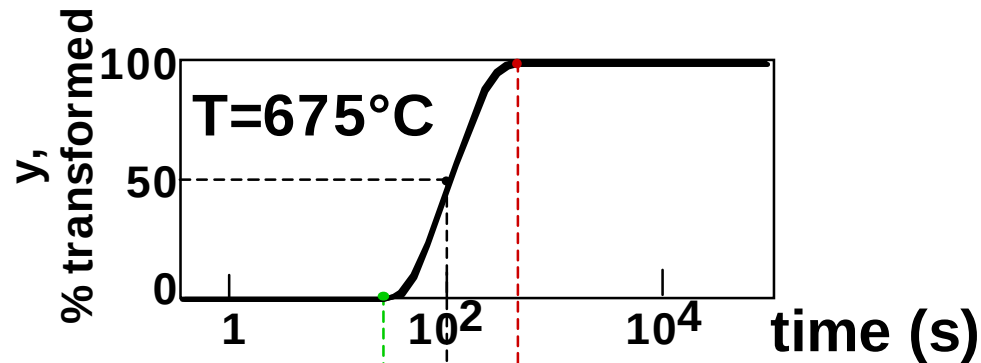


- Examples:



ISOTHERMAL TRANSFORMATION DIAGRAMS

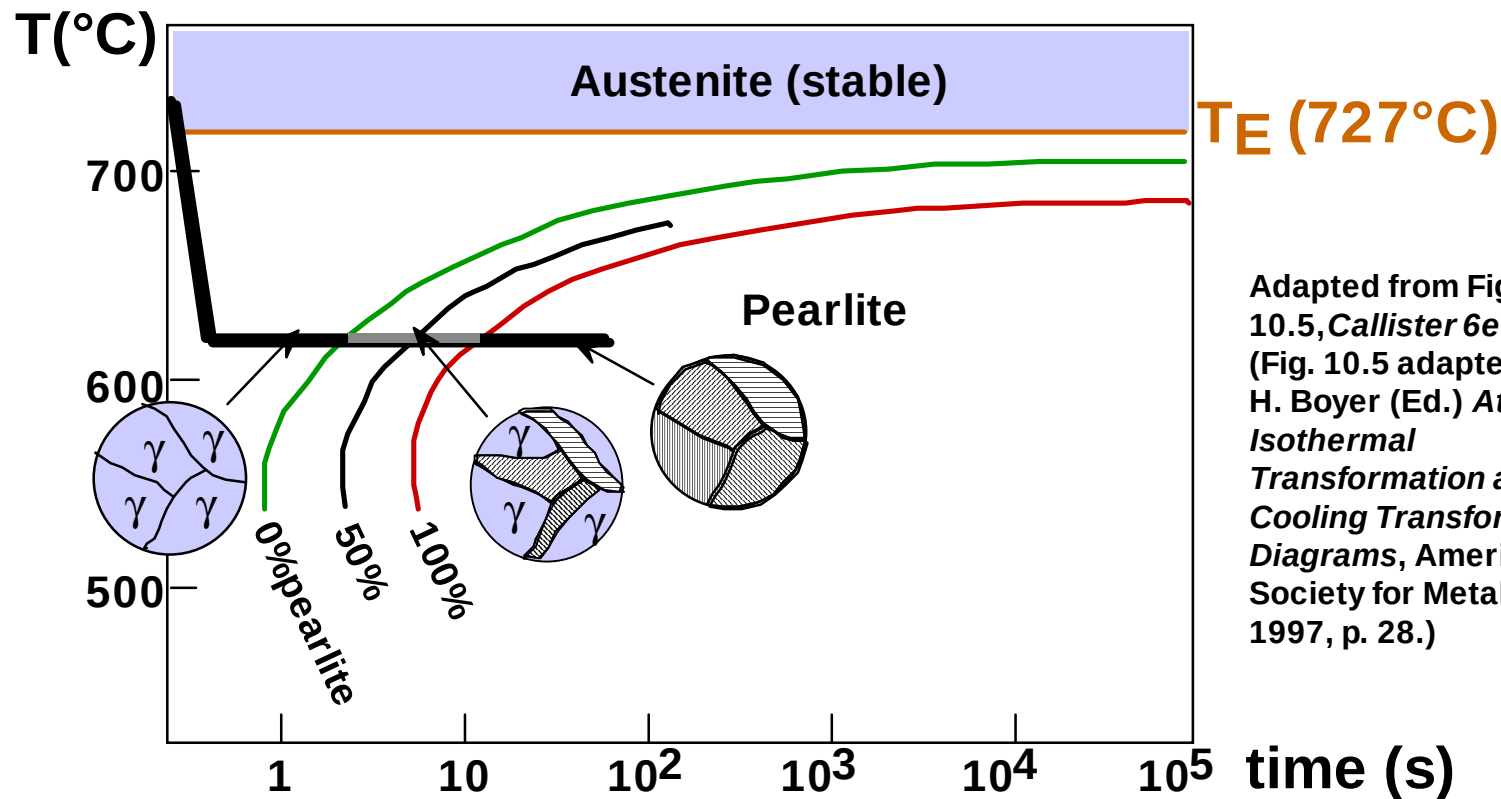
- Fe-C system, $C_0 = 0.77\text{wt}\%C$
- Transformation at $T = 675^\circ\text{C}$.



Adapted from Fig. 10.4, *Callister 6e*.
(Fig. 10.4 adapted from H. Boyer (Ed.)
*Atlas of Isothermal Transformation
and Cooling Transformation Diagrams*,
American Society for Metals, 1977, p.
369.)

EX: COOLING HISTORY Fe-C SYSTEM

- Eutectoid composition, $C_0 = 0.77\text{wt}\%C$
- Begin at $T > 727^\circ\text{C}$
- Rapidly cool to 625°C and hold isothermally.



Adapted from Fig. 10.5, Callister 6e. (Fig. 10.5 adapted from H. Boyer (Ed.) *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, 1997, p. 28.)

PEARLITE MORPHOLOGY

Two cases:

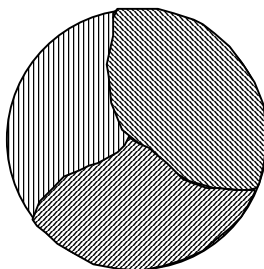
- T_{transf} just below T_E
 - Larger T : diffusion is faster
 - Pearlite is coarser.
- T_{transf} well below T_E
 - Smaller T : diffusion is slower
 - Pearlite is finer.



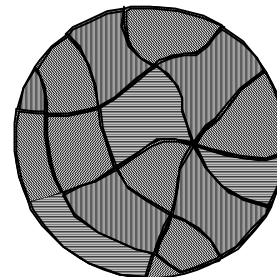
10 μm



Adapted from Fig. 10.6 (a) and (b), *Callister 6e*. (Fig. 10.6 from R.M. Ralls et al., *An Introduction to Materials Science and Engineering*, p. 361, John Wiley and Sons, Inc., New York, 1976.)



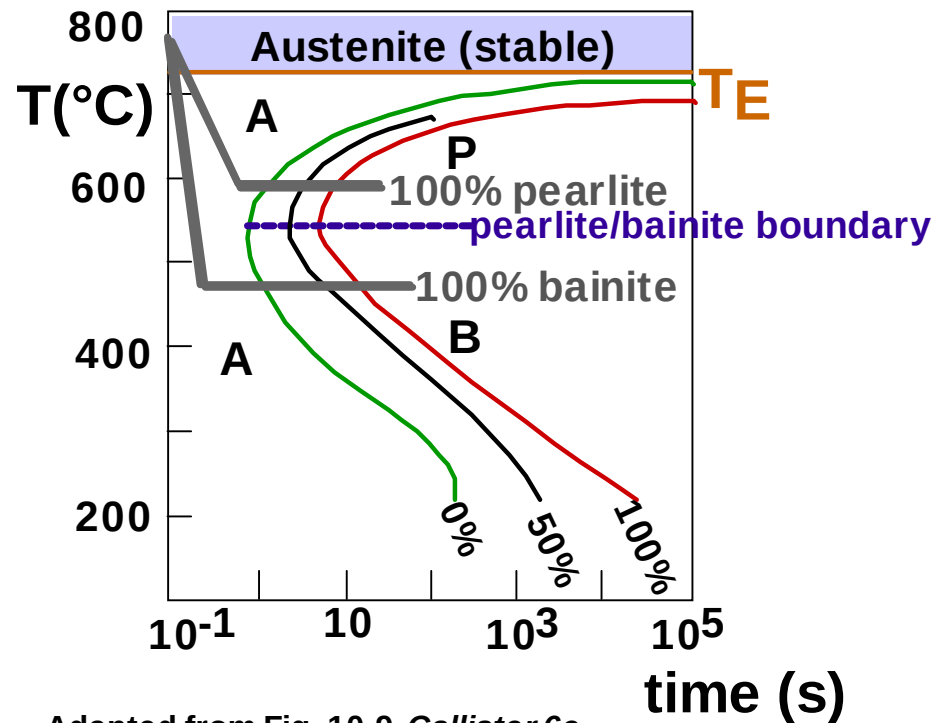
- Smaller ΔT :
colonies are
larger



- Larger ΔT :
colonies are
smaller

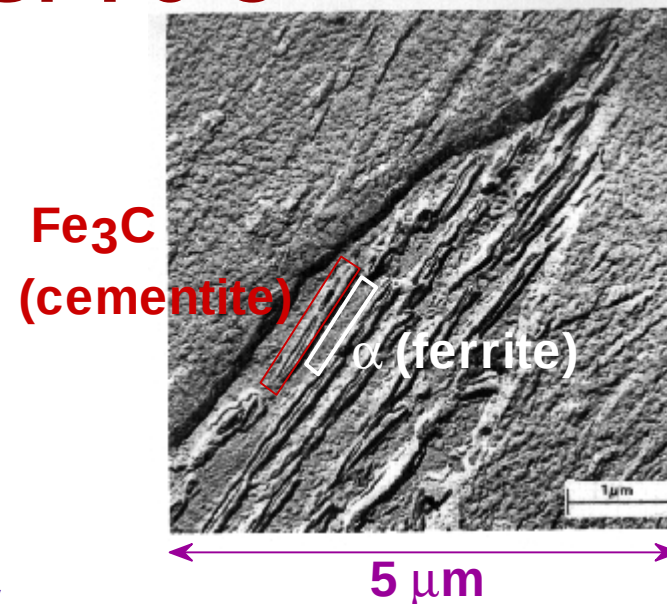
NON-EQUIL TRANSFORMATION PRODUCTS: Fe-C

- **Bainite:**
 - α lathes (strips) with long rods of Fe_3C
 - diffusion controlled.
- Isothermal Transf. Diagram



Adapted from Fig. 10.9, Callister 6e.

(Fig. 10.9 adapted from H. Boyer (Ed.) *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, 1997, p. 28.)



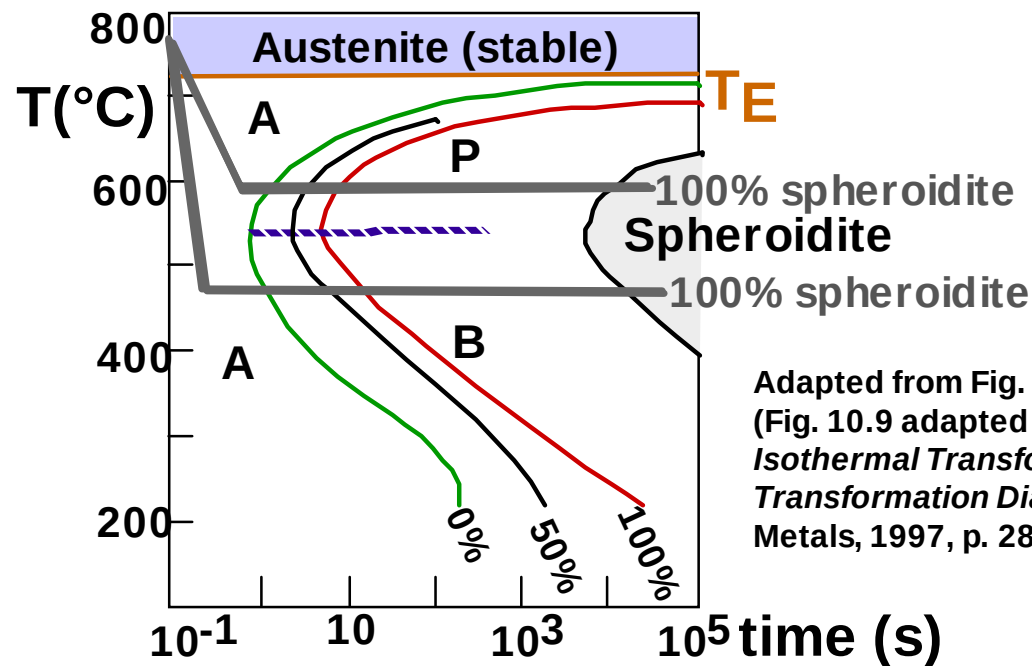
(Adapted from Fig. 10.8, Callister, 6e. (Fig. 10.8 from *Metals Handbook*, 8th ed., Vol. 8, *Metallography, Structures, and Phase Diagrams*, American Society for Metals, Materials Park, OH, 1973.)

Bainite reaction rate:

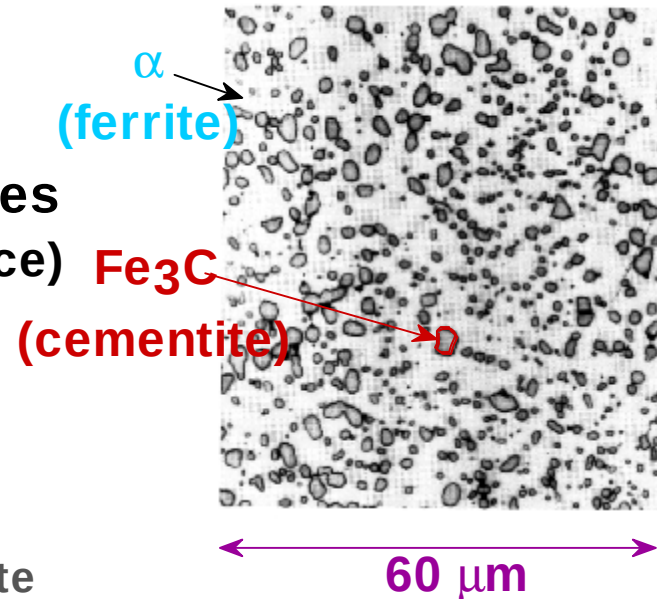
$$r_{\text{bainite}} = e^{-Q/RT}$$

OTHER PRODUCTS: Fe-C SYSTEM (1)

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



Adapted from Fig. 10.9, Callister 6e.
(Fig. 10.9 adapted from H. Boyer (Ed.) *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, 1997, p. 28.)

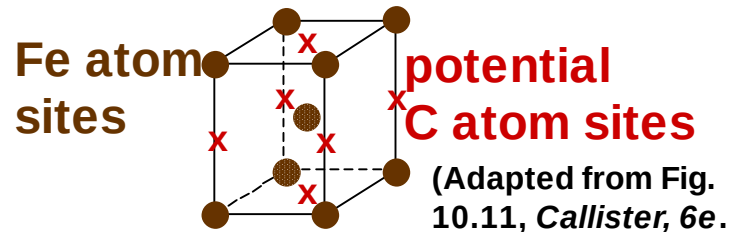


(Adapted from Fig. 10.10, Callister, 6e. (Fig. 10.10 copyright United States Steel Corporation, 1971.)

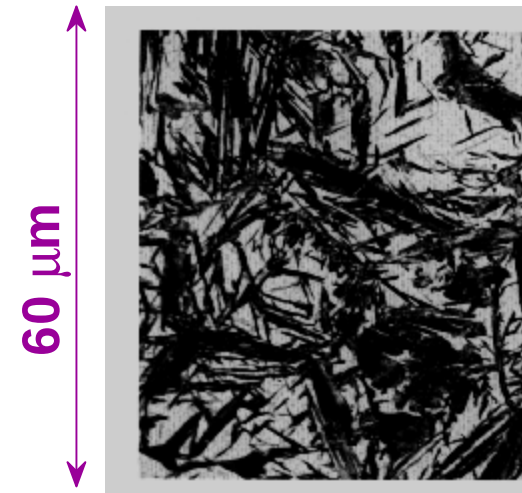
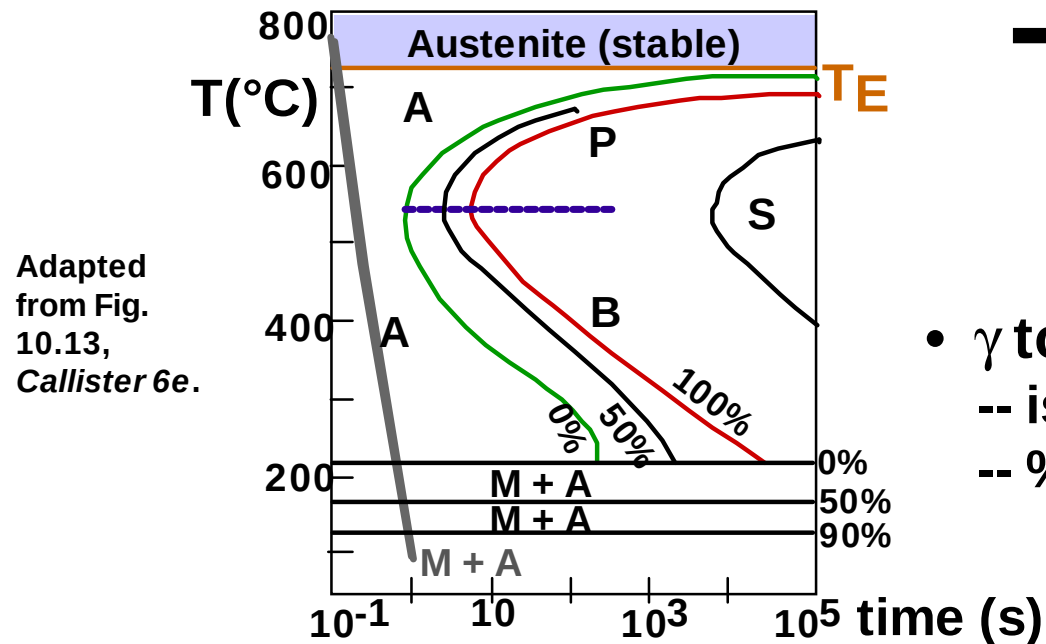
OTHER PRODUCTS: Fe-C SYSTEM (2)

- Martensite:**

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



- Isothermal Transf. Diagram**



— Martensite needles
— Austenite

(Adapted from Fig. 10.12, Callister, 6e. (Fig. 10.12 courtesy United States Steel Corporation.))

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

COOLING EX: Fe-C SYSTEM (1)

- $C_0 = C_{\text{eutectoid}}$
- Three histories...

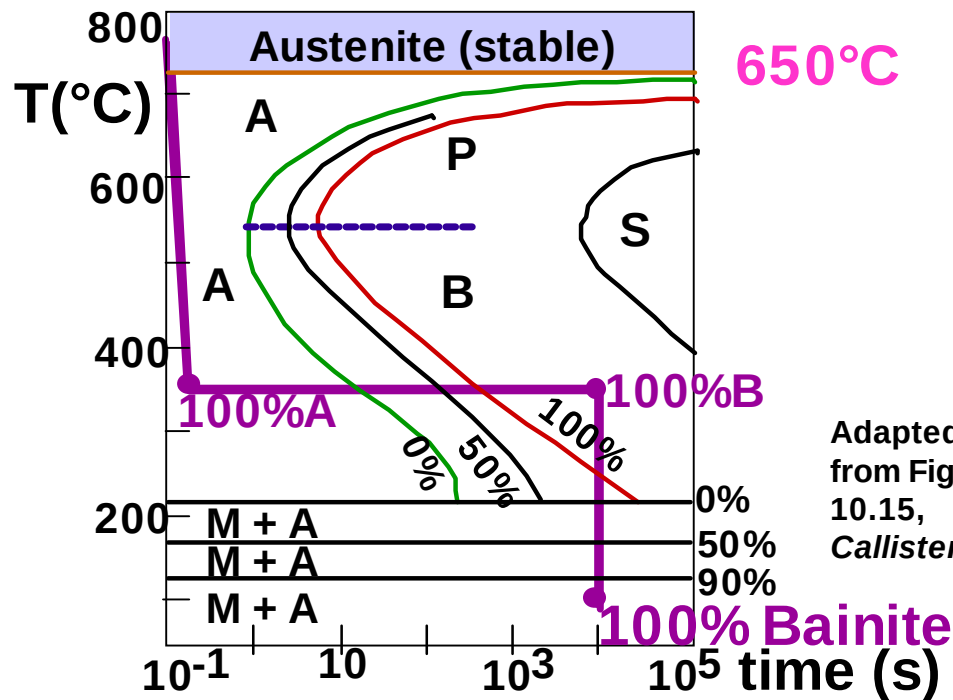
Rapid Hold Rapid Hold Rapid
cool to: for: cool to: for: cool to:

350°C 10^4 s T_{room}

250°C 10^2 s T_{room}

650°C 20s 400°C 10^3 s T_{room}

Case I



COOLING EX: Fe-C SYSTEM (2)

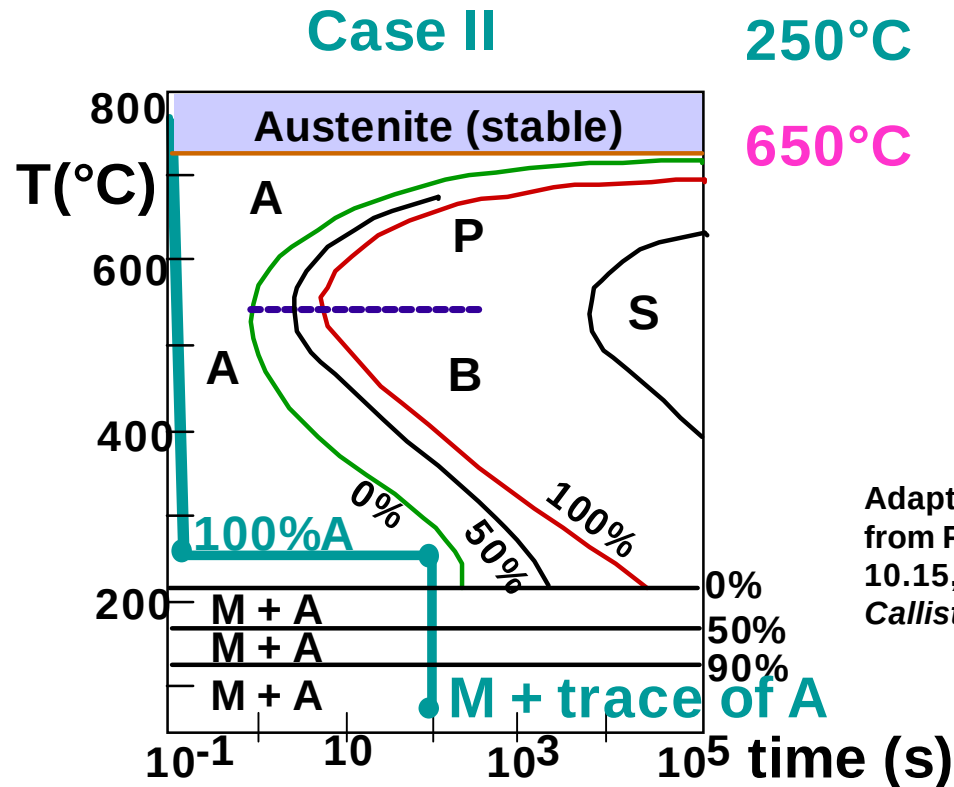
- $C_0 = C_{\text{eutectoid}}$
- Three histories...

Rapid cool to: Hold for: Rapid cool to: Hold for: Rapid cool to:

350°C 10⁴s T_{room}

250°C 10²s T_{room}

650°C 20s 400°C 10³s T_{room}



COOLING EX: Fe-C SYSTEM (3)

- $C_0 = C_{\text{eutectoid}}$
- Three histories...

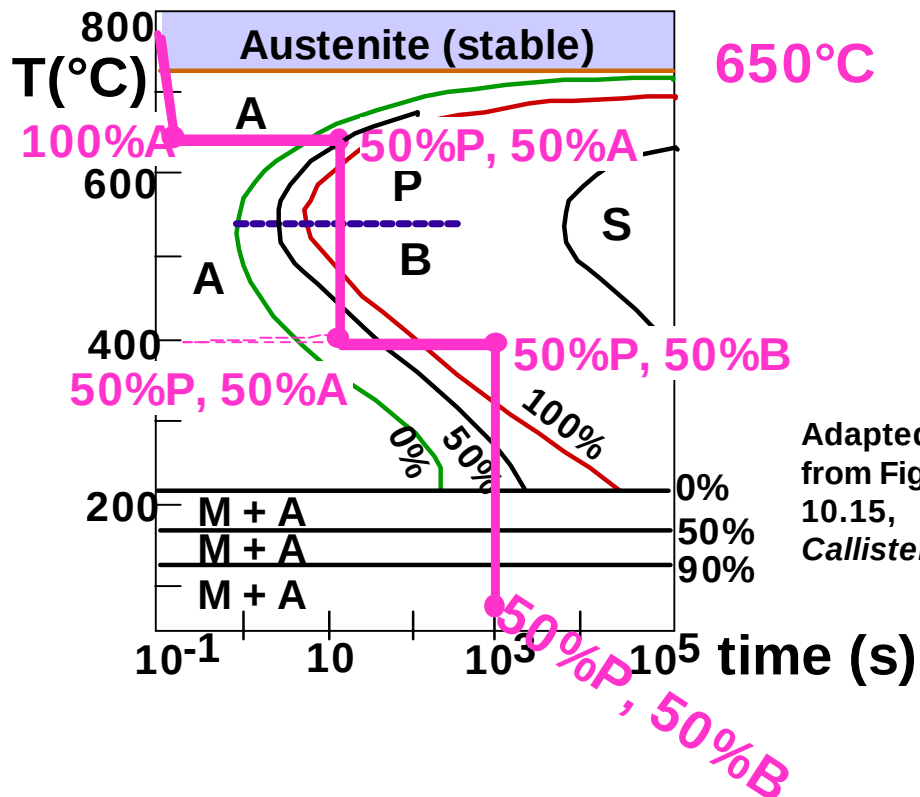
Rapid Hold Rapid Hold Rapid
cool to: for: cool to: for: cool to:

350°C 10^4 s T_{room}

250°C 10^2 s T_{room}

650°C 20s 400°C 10^3 s T_{room}

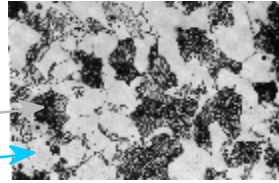
Case III



MECHANICAL PROP: Fe-C SYSTEM (1)

- Effect of wt%C

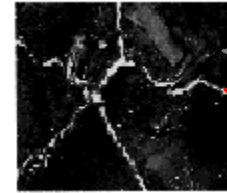
Pearlite (med)
ferrite (soft)



$C_0 < 0.77 \text{ wt}\% \text{C}$

Hypoeutectoid

Adapted from Fig. 9.27, Callister 6e. (Fig. 9.27 courtesy Republic Steel Corporation.)

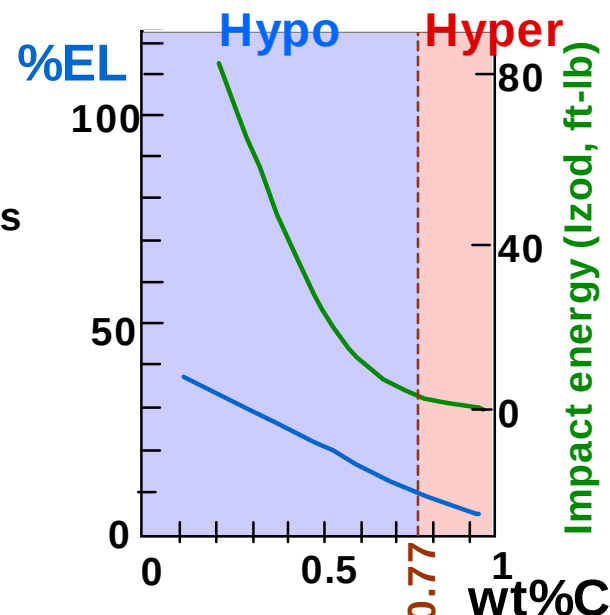
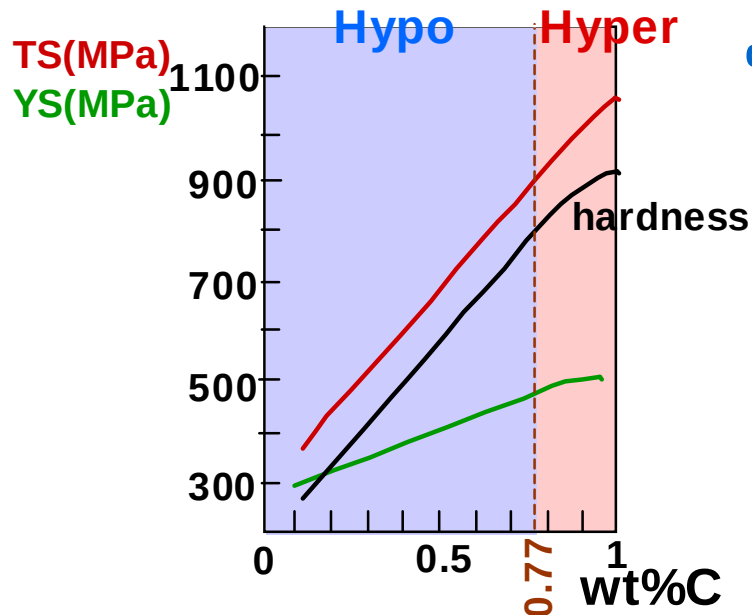


Pearlite (med)
Cementite (hard)

$C_0 > 0.77 \text{ wt}\% \text{C}$

Hypereutectoid

Adapted from Fig. 9.30, Callister 6e. (Fig. 9.30 copyright 1971 by United States Steel Corporation.)

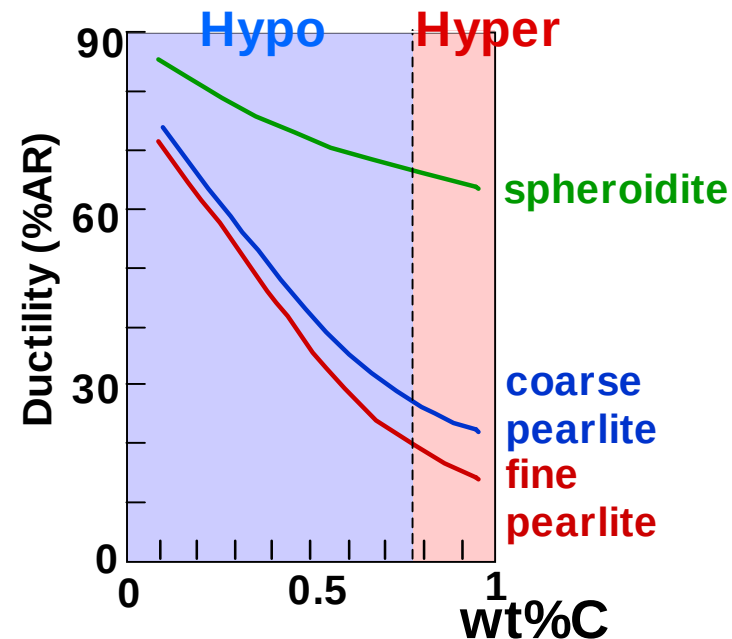
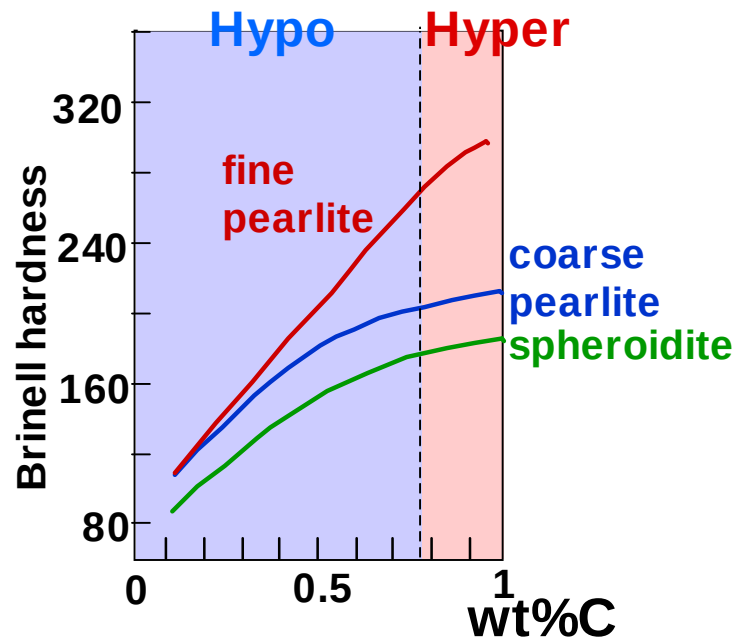


Adapted from Fig. 10.20, Callister 6e. (Fig. 10.20 based on data from *Metals Handbook: Heat Treating*, Vol. 4, 9th ed., V. Masseria (Managing Ed.), American Society for Metals, 1981, p. 9.)

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

MECHANICAL PROP: Fe-C SYSTEM (2)

- Fine vs coarse pearlite vs spheroidite

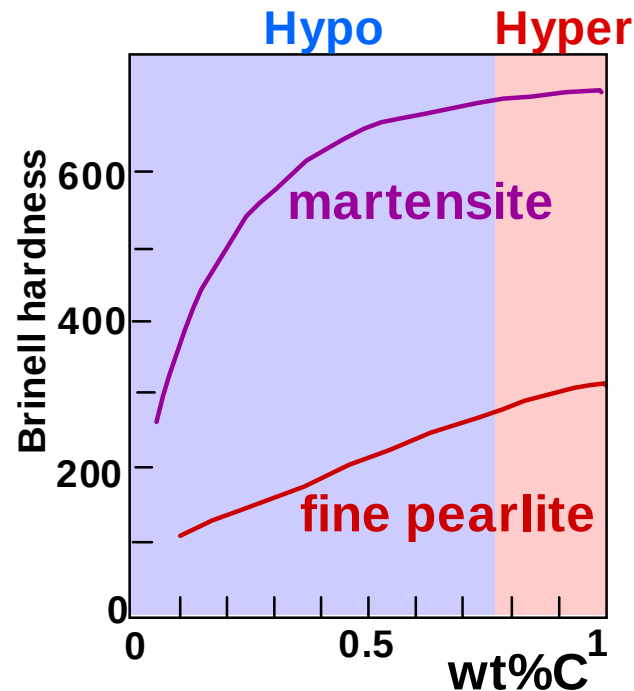


- Hardness: fine > coarse > spheroidite
- %AR: fine < coarse < spheroidite

Adapted from Fig. 10.21, *Callister* 6e. (Fig. 10.21 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:

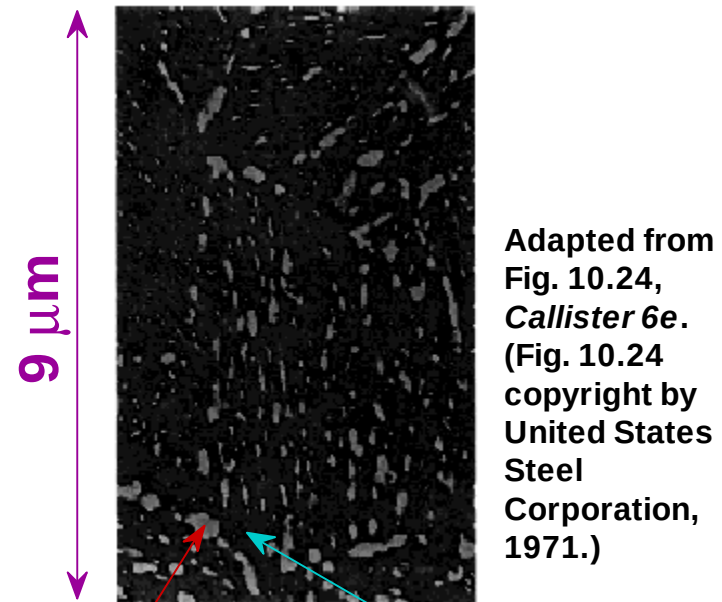
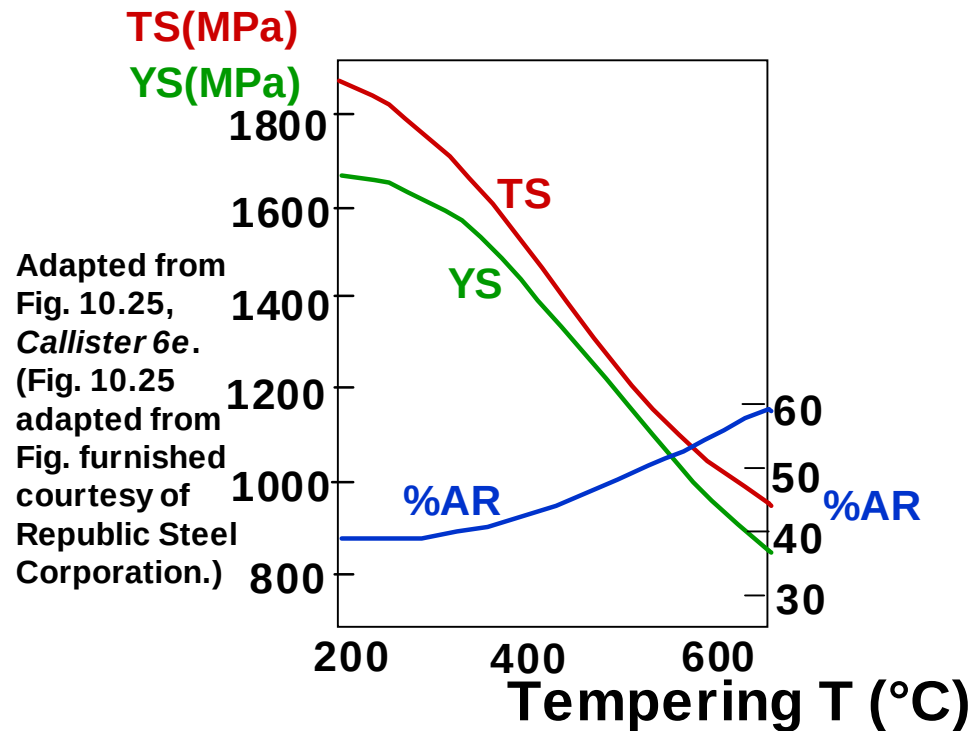


Adapted from Fig. 10.23, *Callister 6e*. (Fig. 10.23 adapted from Edgar C. Bain, *Functions of the Alloying Elements in Steel*, American Society for Metals, 1939, p. 36; and R.A. Grange, C.R. Hribal, and L.F. Porter, *Metall. Trans. A*, Vol. 8A, p. 1776.)

- Hardness: fine pearlite << martensite.

TEMPERING MARTENSITE

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



- produces extremely small **Fe₃C particles** surrounded by **α**.
- decreases TS, YS but increases %AR

SUMMARY: PROCESSING OPTIONS

