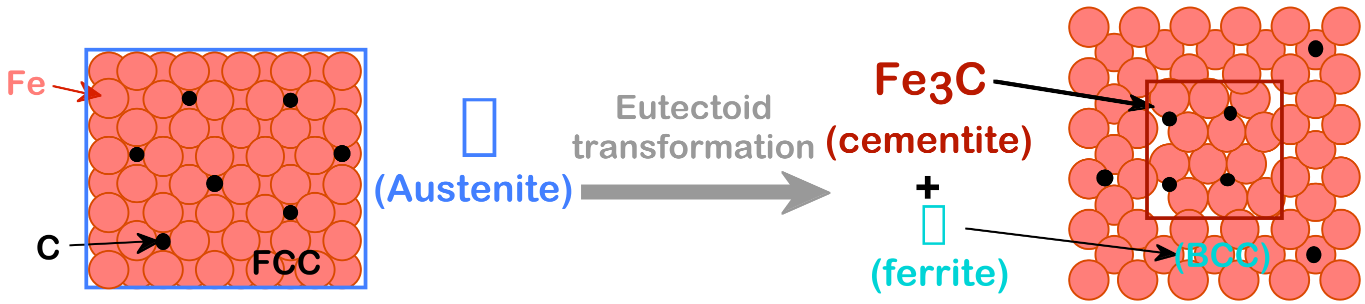
CHAPTER 10: PHASE TRANSFORMATIONS

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?

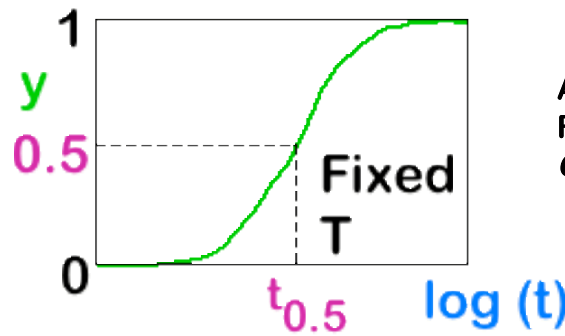
FRACTION OF TRANSFORMATION

- **Fraction transformed depends on time.**

Avrami Eqn.

$$y = 1 - e^{-kt^n}$$

fraction transformed (y); time (t)



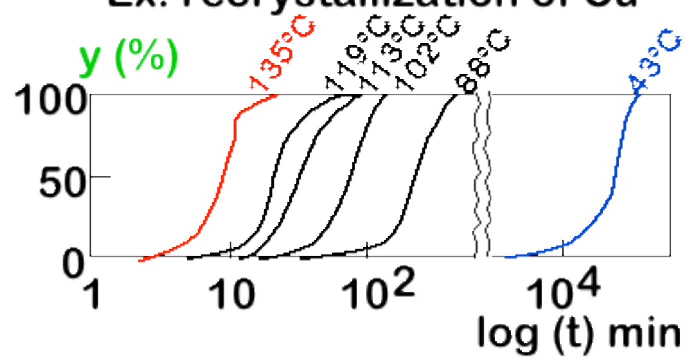
Adapted from Fig. 10.1, *Callister 6e.*

- **Transformation rate depends on T.**

activation energy

$$r = \frac{1}{t_{0.5}} = Ae^{-Q/RT}$$

Ex: recrystallization of Cu

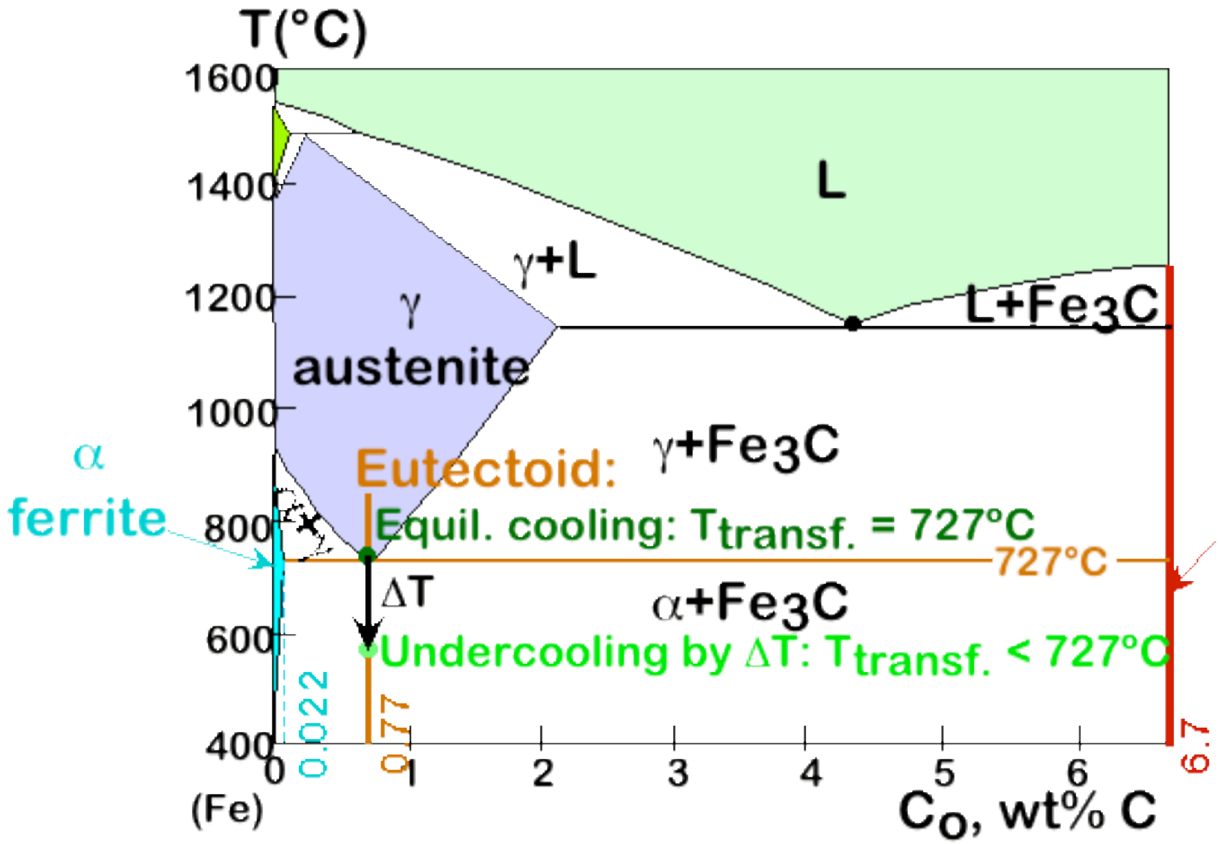


Adapted from Fig. 10.2, *Callister 6e.* (Fig. 10.2 adapted from B.F. Decker and D. Harker, "Recrystallization in Rolled Copper", *Trans AIME*, 188, 1950, p. 888.)

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

TRANSFORMATIONS & UNDERCOOLING

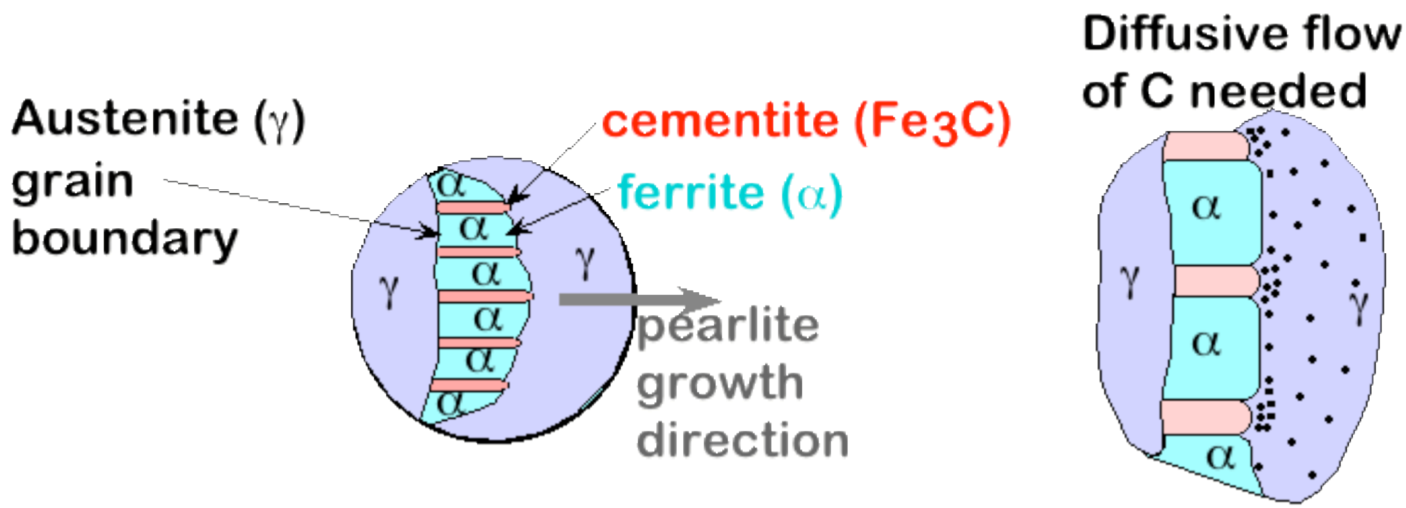
- Eutectoid transf. (Fe-C System): $\gamma \Rightarrow \alpha + Fe_3C$ (0.77wt%C → 0.022wt%C + 6.7wt%C)
- Can make it occur at:
  - ...727°C (cool it slowly)
  - ...below 727°C ("undercool" it!)



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.)

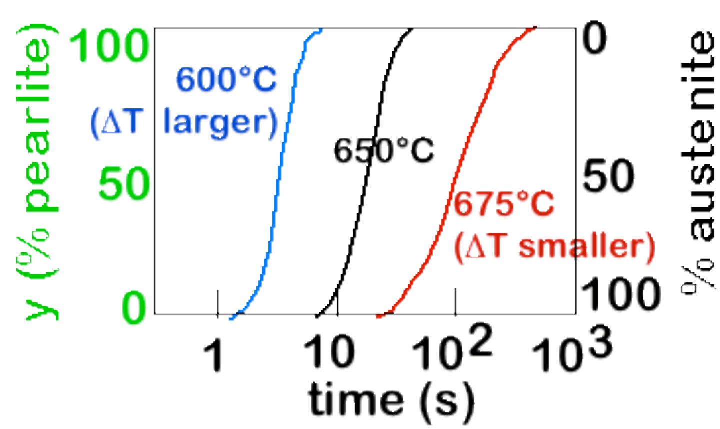
EUTECTOID TRANSFORMATION RATE ~ ΔT

- Growth of pearlite from austenite:



Adapted from Fig. 9.13, *Callister 6e.*

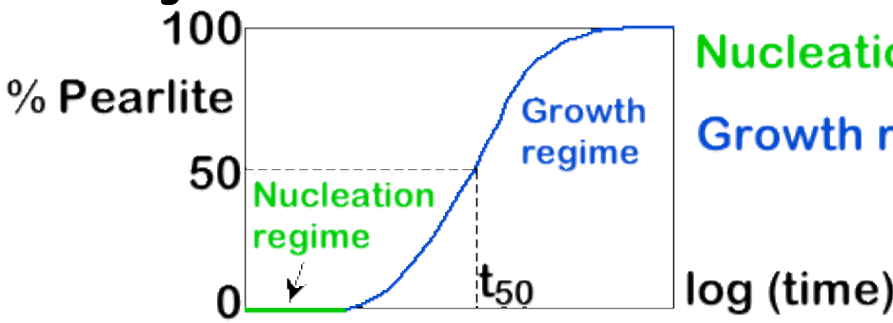
- Reaction rate increases with ΔT.



Adapted from Fig. 10.3, *Callister 6e.*

NUCLEATION AND GROWTH

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

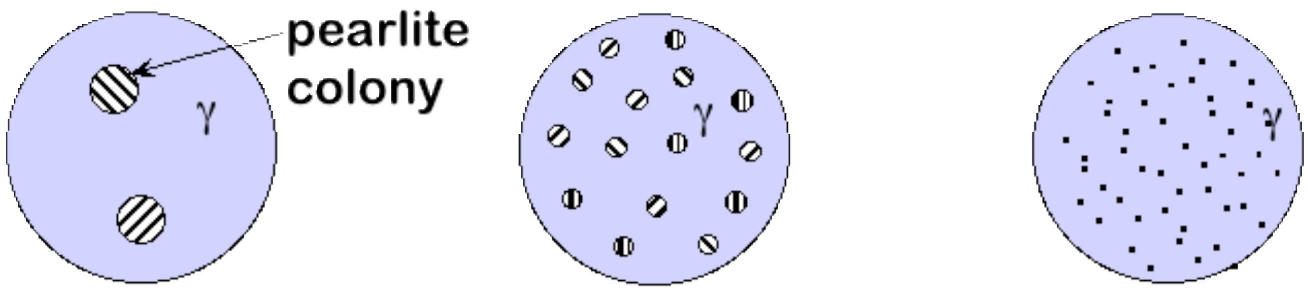


Nucleation rate increases w/ ΔT

Growth rate increases w/ T

Adapted from Fig. 10.1, *Callister 6e*.

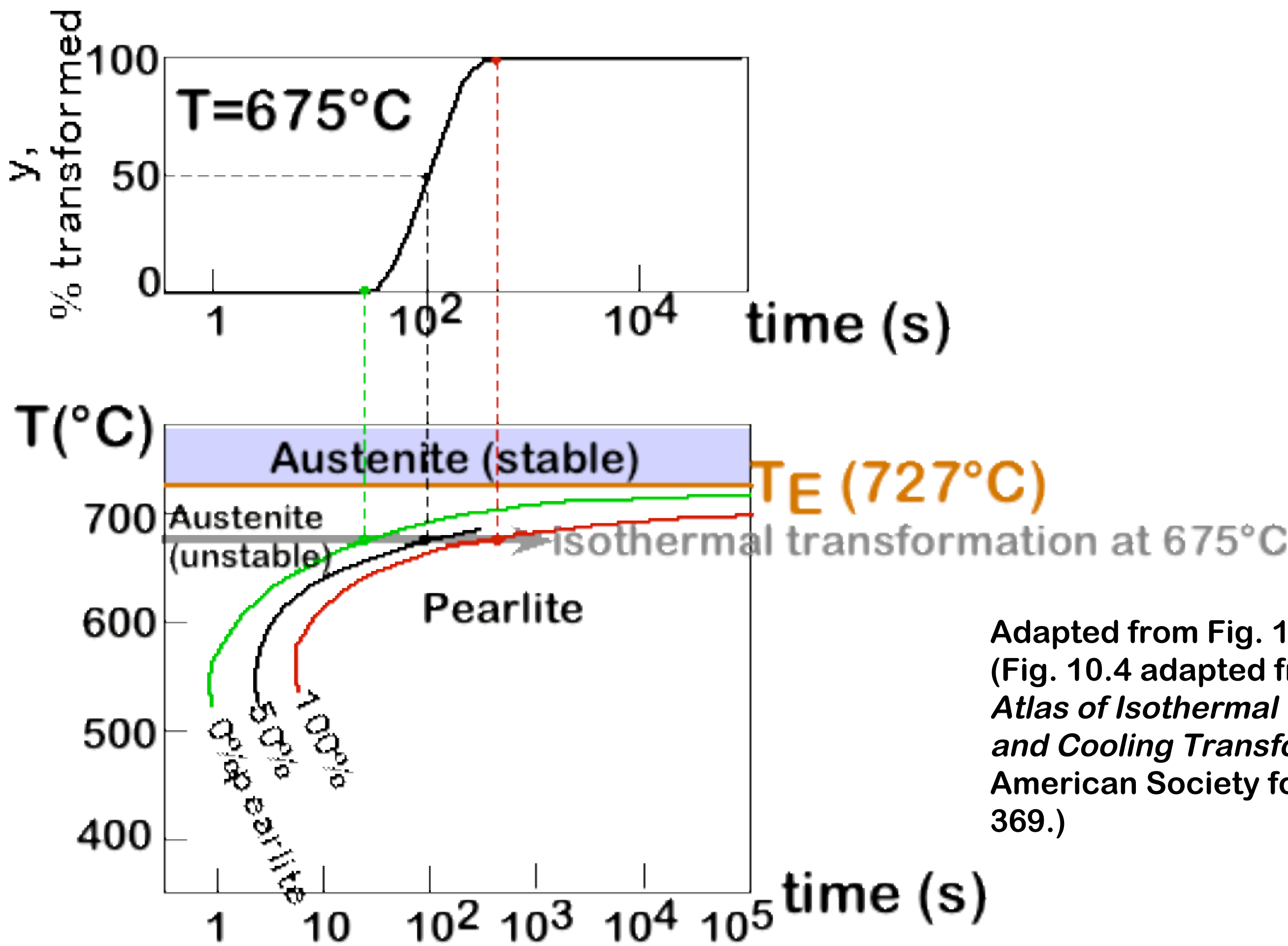
- Examples:



T just below T_E	T moderately below T_E	T way below T_E
Nucleation rate low	Nucleation rate med .	Nucleation rate high
Growth rate high	Growth rate med.	Growth rate low

ISOTHERMAL TRANSFORMATION DIAGRAMS

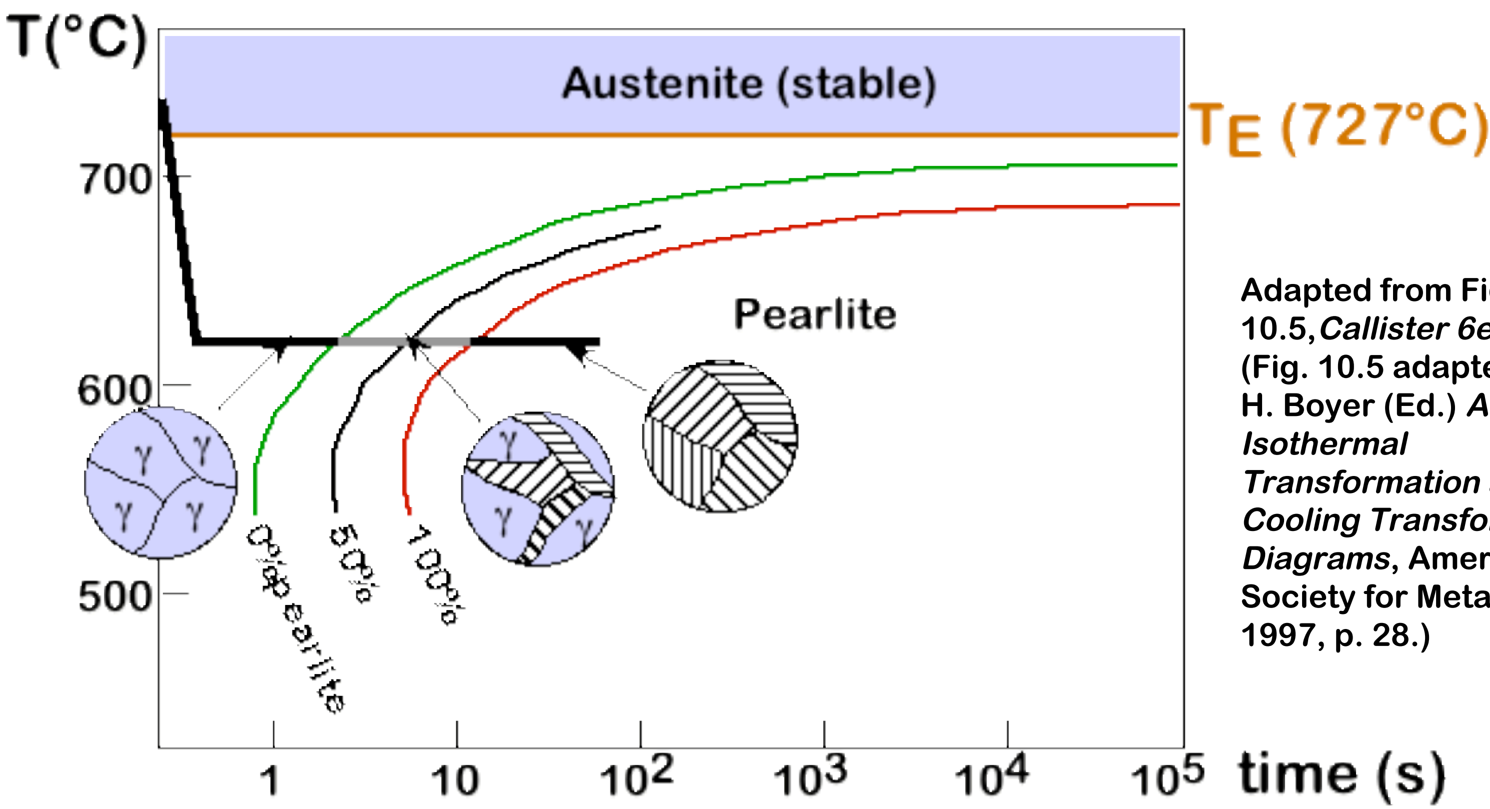
- Fe-C system, C_o = 0.77wt%C
- Transformation at T = 675C.



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_o = 0.77wt%C
- Begin at T > 727C
- Rapidly cool to 625C and hold isothermally.

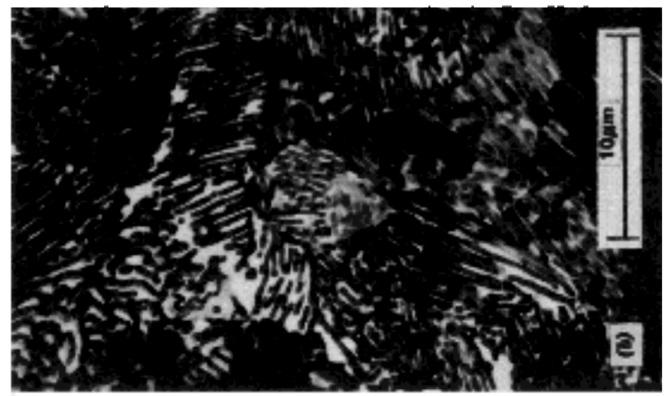


Adapted from Fig. 10.5, *Callister 6e.* (Fig. 10.5 adapted from H. Boyer (Ed.) *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, 1997, p. 28.)

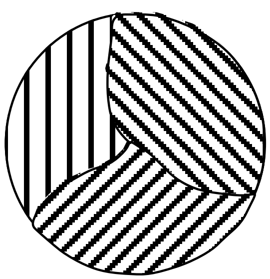
PEARLITE MORPHOLOGY

Two cases:

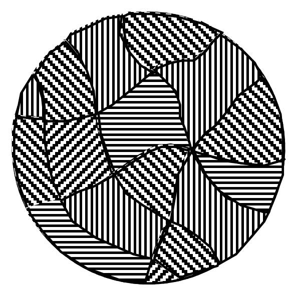
- T_{transf} just below T_E
  - --Larger T: diffusion is faster
  - --Pearlite is coarser.
- T_{transf} well below T_E
  - --Smaller T: diffusion is slower
  - --Pearlite is finer.



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.)



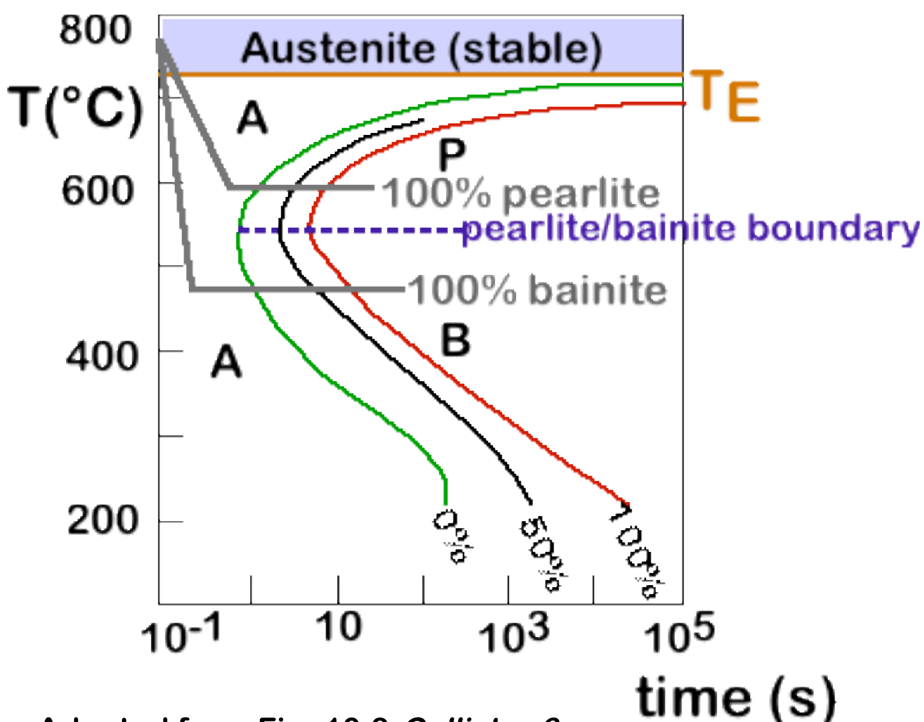
- Smaller ΔT: colonies are larger



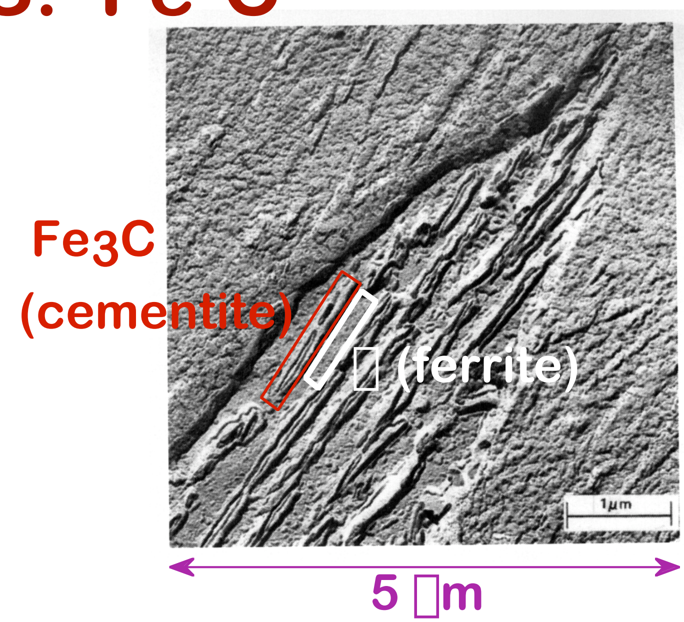
- Larger ΔT: colonies are smaller

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.)



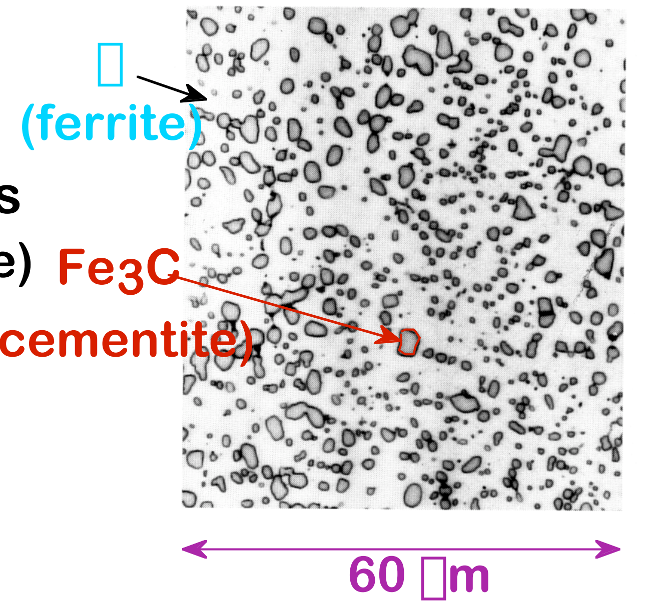
(Adapted from Fig. 10.8, *Callister, 6e*.
(Fig. 10.8 from *Metals Handbook*, 8th ed., Vol. 8, *Metallography, Structures, and Phase Diagrams*, American Society for Metals, Materials Park, OH, 1973.)

Bainite reaction rate:

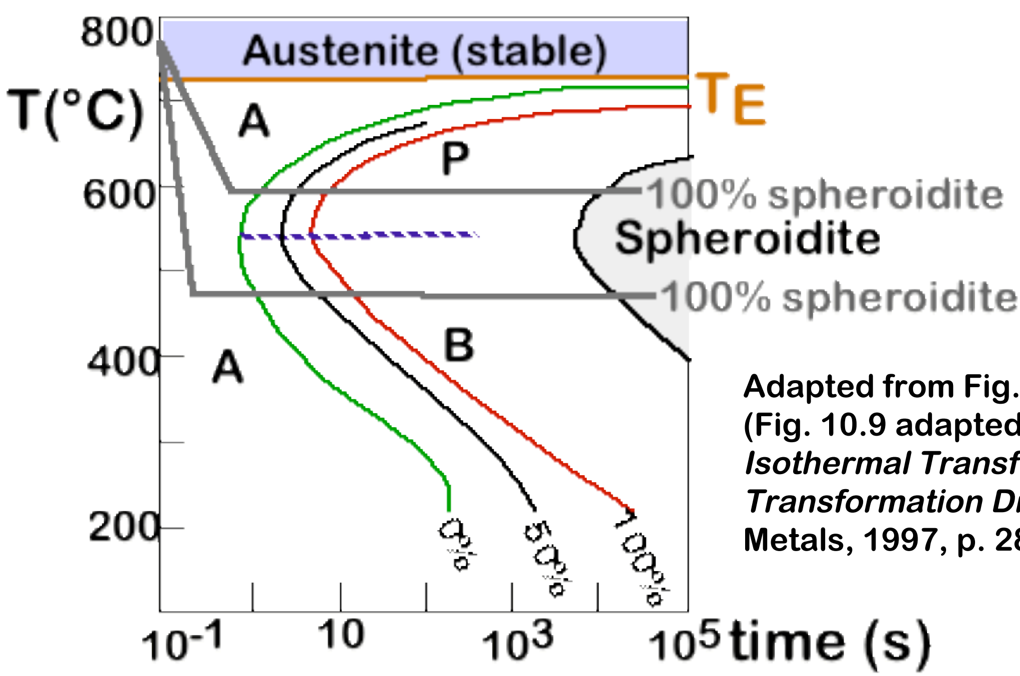
$$r_{bainite} = e^{-Q/RT}$$

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**



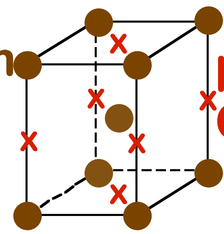
(Adapted from Fig. 10.10, *Callister, 6e.* (Fig. 10.10 copyright United States Steel Corporation, 1971.)



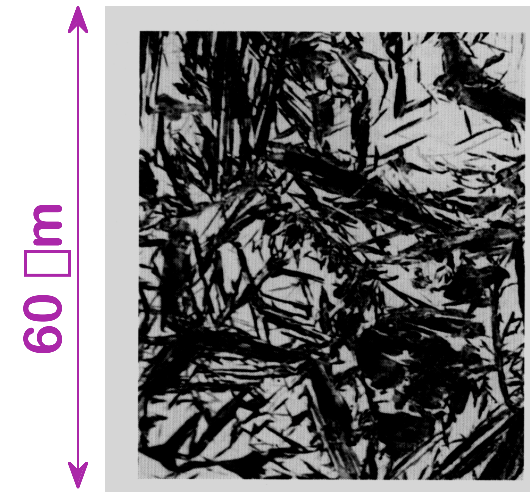
Adapted from Fig. 10.9, *Callister 6e.* (Fig. 10.9 adapted from H. Boyer (Ed.) *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, 1997, p. 28.)

OTHER PRODUCTS: Fe-C SYSTEM (2)

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

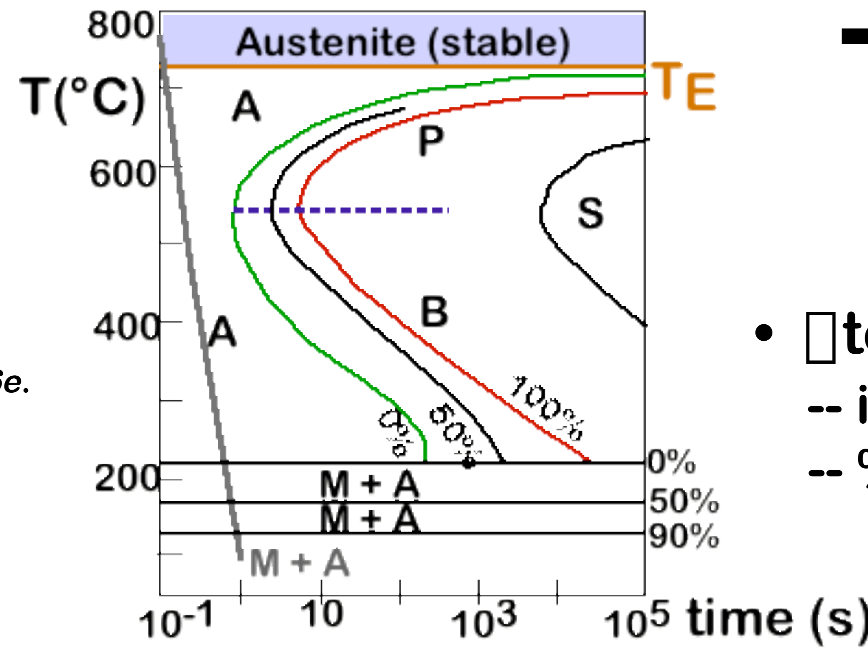


(Adapted from Fig. 10.11, *Callister, 6e*.)



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

- **Isothermal Transf. Diagram**



Adapted from Fig. 10.13, *Callister 6e*.

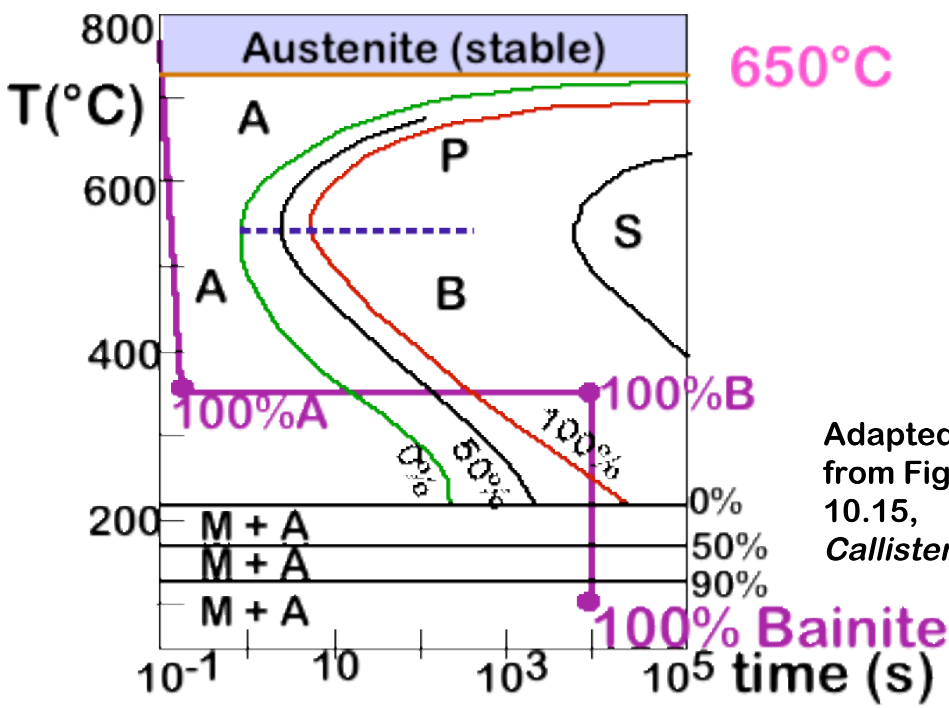
- γ to M transformation..
  -- is rapid!
  -- % transf. depends on T only.

COOLING EX: Fe-C SYSTEM (1)

- $C_o = C_{eutectoid}$
- Three histories...

Rapid cool to:	Hold for:	Rapid cool to:	Hold for:	Rapid cool to:
350°C	10^4s	T_{room}		
250°C	10^2s	T_{room}		
650°C	20s	400°C	10^3s	T_{room}

Case I



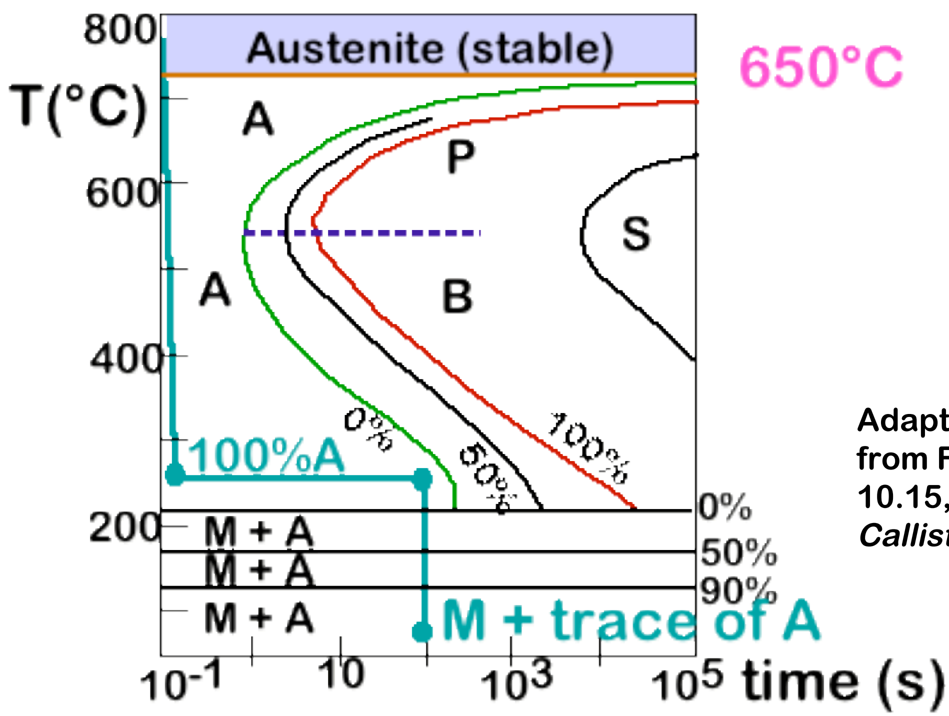
Adapted from Fig. 10.15, *Callister 6e.*

COOLING EX: Fe-C SYSTEM (2)

- $C_o = C_{eutectoid}$
- Three histories...

Rapid cool to:	Hold for:	Rapid cool to:	Hold for:	Rapid cool to:
350°C	10^4s	T_{room}		
250°C	10^2s	T_{room}		
650°C	20s	400°C	10^3s	T_{room}

Case II



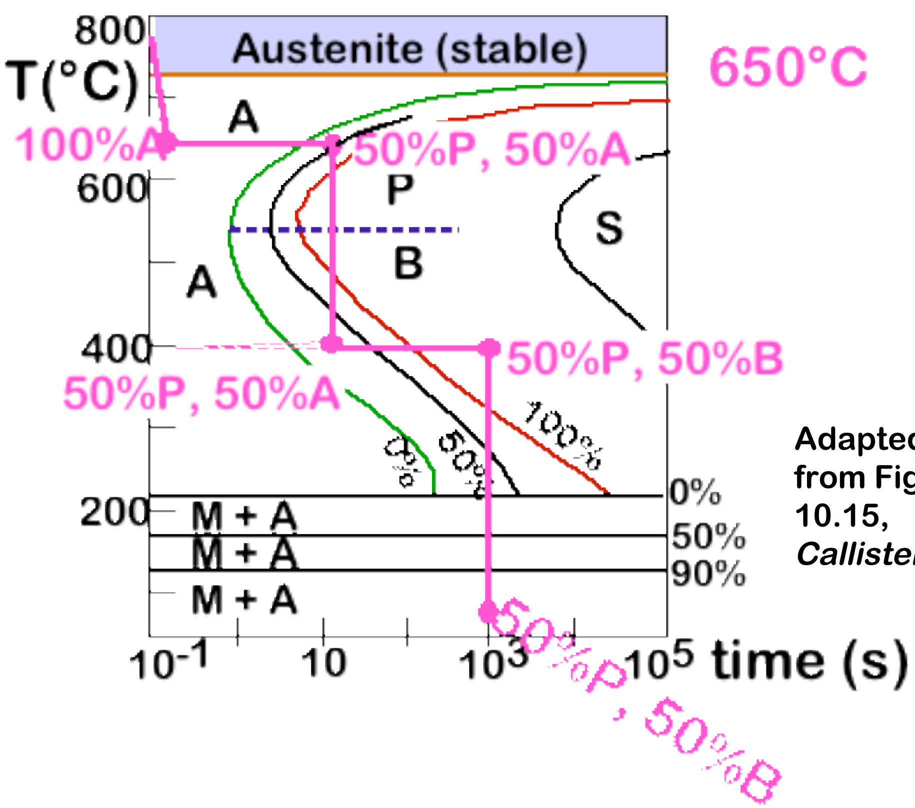
Adapted from Fig. 10.15, *Callister 6e.*

COOLING EX: Fe-C SYSTEM (3)

- $C_o = C_{eutectoid}$
- Three histories...

Rapid cool to:	Hold for:	Rapid cool to:	Hold for:	Rapid cool to:
350°C	10^4s	T_{room}		
250°C	10^2s	T_{room}		
650°C	20s	400°C	10^3s	T_{room}

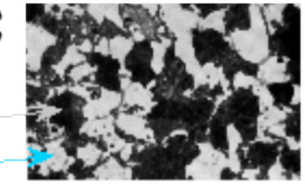
Case III



Adapted from Fig. 10.15, *Callister 6e.*

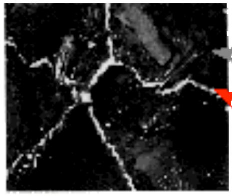
MECHANICAL PROP: Fe-C SYSTEM (1)

- Effect of wt%C



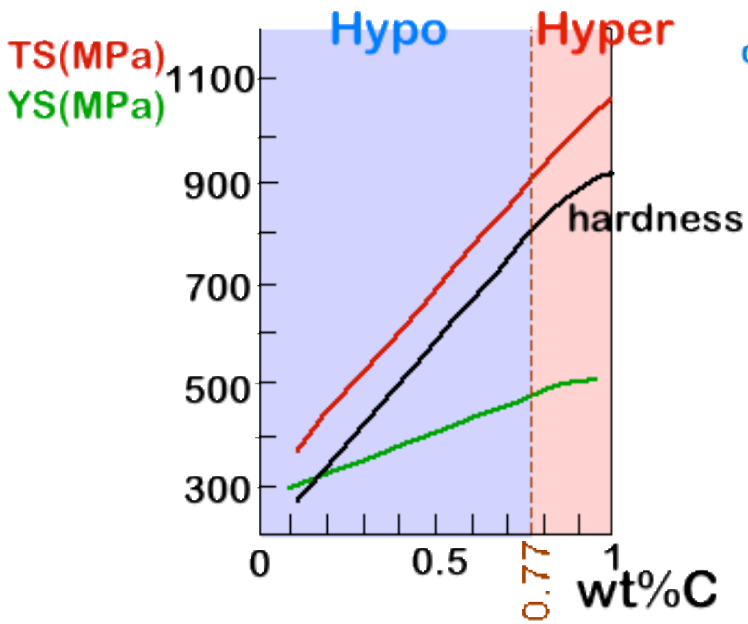
C_o<0.77wt%C
Hypoeutectoid

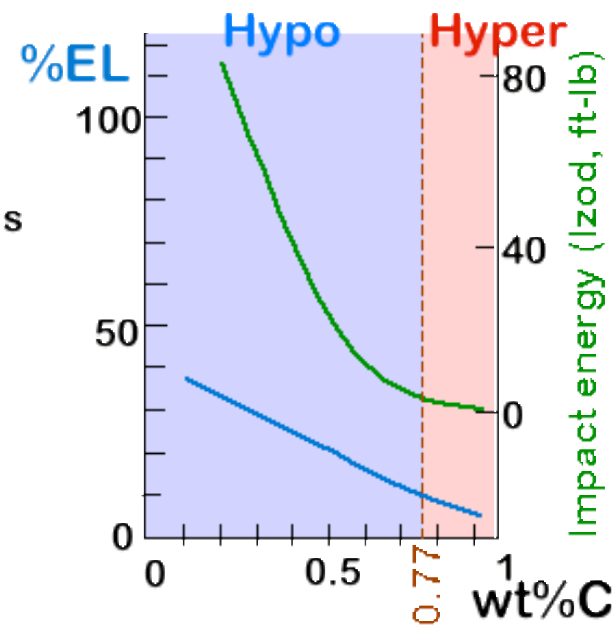
Adapted from Fig. 9.27, *Callister 6e*. (Fig. 9.27 courtesy Republic Steel Corporation.)



C_o>0.77wt%C
Hypereutectoid

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



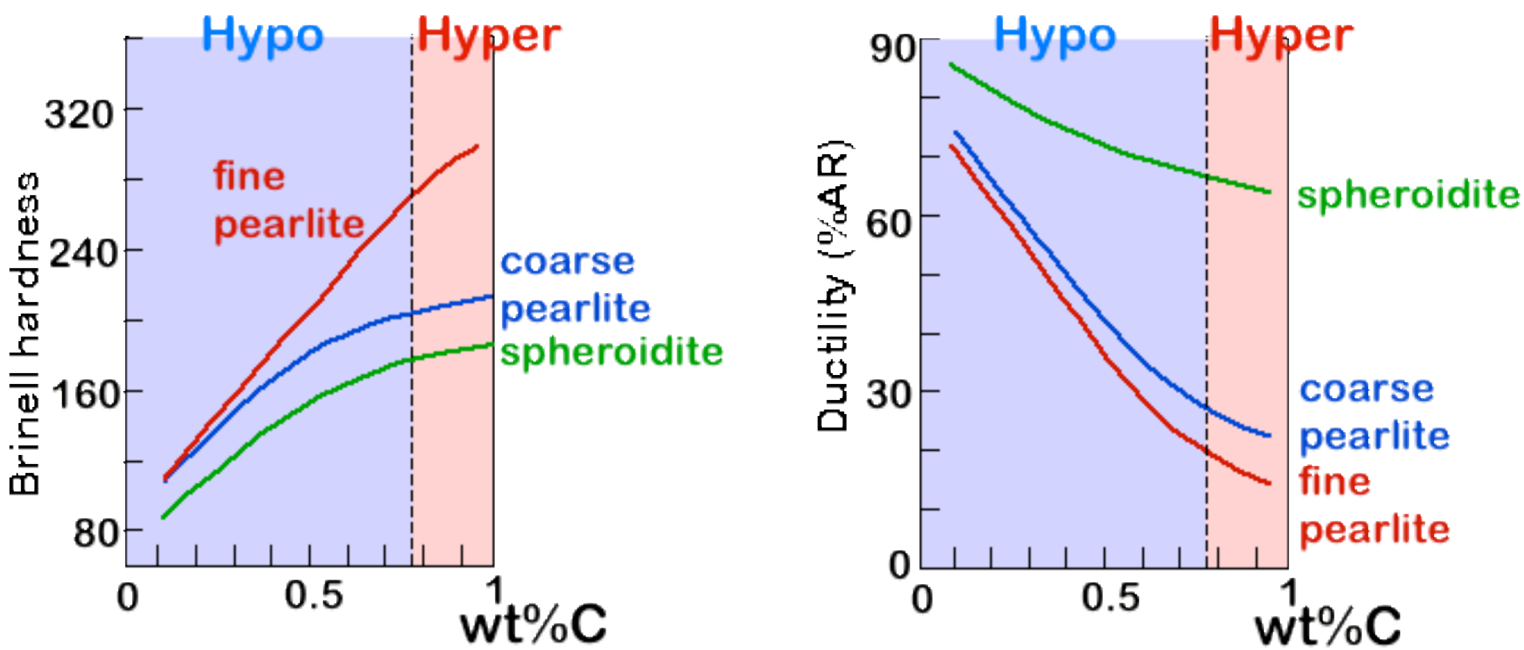


Adapted from Fig. 10.20, *Callister 6e*. (Fig. 10.20 based on data from *Metals Handbook: Heat Treating*, Vol. 4, 9th ed., V. Masseria (Managing Ed.), American Society for Metals, 1981, p. 9.)

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

MECHANICAL PROP: Fe-C SYSTEM (2)

- Fine vs coarse pearlite vs spheroidite

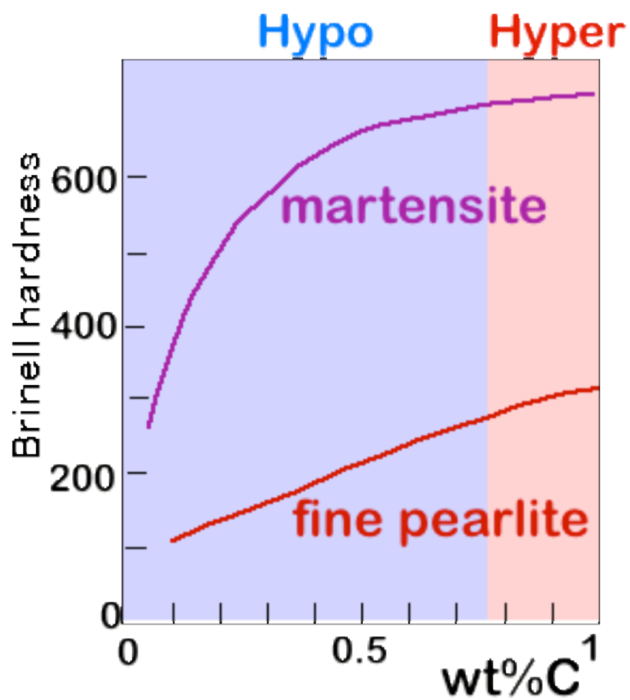


- Hardness: fine > coarse > spheroidite
- %AR: fine < coarse < spheroidite

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:**

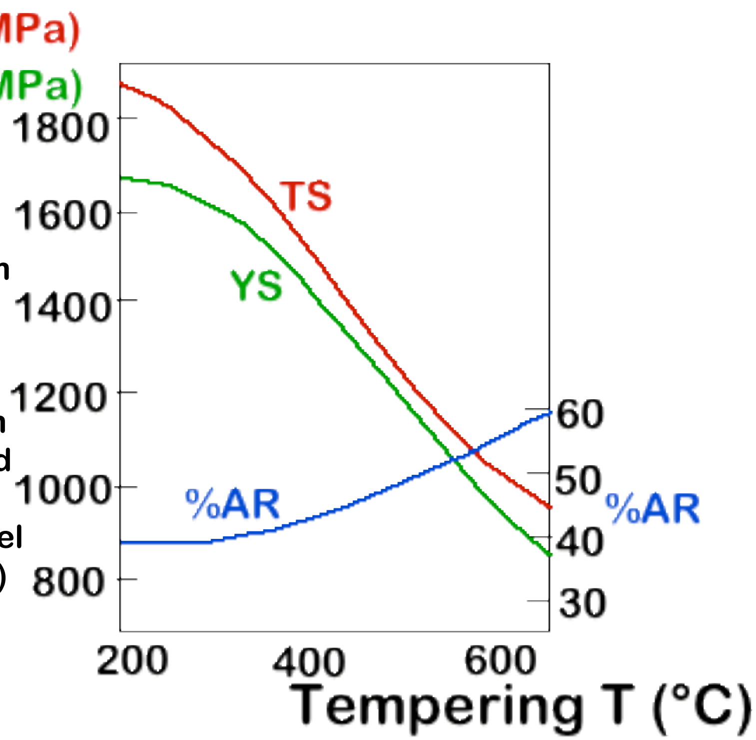


Adapted from Fig. 10.23, *Callister 6e*. (Fig. 10.23 adapted from Edgar C. Bain, *Functions of the Alloying Elements in Steel*, American Society for Metals, 1939, p. 36; and R.A. Grange, C.R. Hribal, and L.F. Porter, *Metall. Trans. A*, Vol. 8A, p. 1776.)

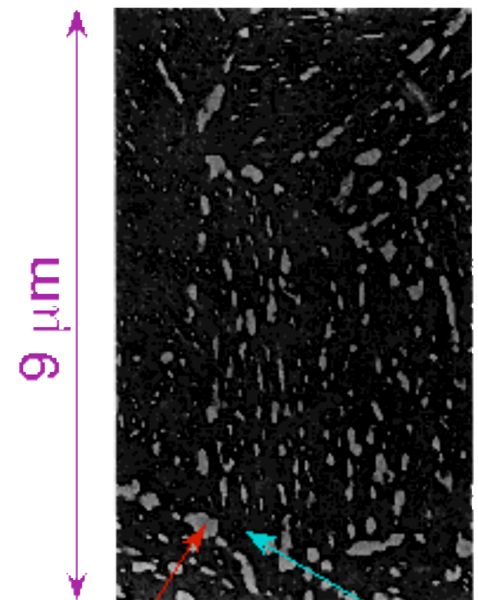
- **Hardness: fine pearlite << martensite.**

TEMPERING MARTENSITE

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



Adapted from Fig. 10.25, *Callister 6e*. (Fig. 10.25 adapted from Fig. furnished courtesy of Republic Steel Corporation.)



Adapted from Fig. 10.24, *Callister 6e*. (Fig. 10.24 copyright by United States Steel Corporation, 1971.)

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

SUMMARY: PROCESSING OPTIONS

Adapted from Fig. 10.27, *Callister 6e.*

Austenite (γ)

slow cool → **Pearlite** (α + Fe_3C layers + a proeutectoid phase)

moderate cool → **Bainite** (α + Fe_3C plates/needles)

rapid quench → **Martensite** (BCT phase diffusionless transformation)

reheat → **Tempered Martensite** (α + very fine Fe_3C particles)

Strength ↑ / Ductility ↓

Martensite
T Martensite
bainite
fine pearlite
coarse pearlite
spheroidite

General Trends

ANNOUNCEMENTS

Reading:

Core Problems:

Self-help Problems: