# Chapter 10: Phase Transformations

**ISSUES TO ADDRESS...**

- _____ one phase into another takes time.


- How does the rate of _____ depend on time and temperature?
- Is it possible to slow down transformations so that non-equilibrium _____ are formed?
- Are the mechanical properties of non-equilibrium structures more desirable than _____ ones?



# Phase Transformations

Nucleation

- nuclei (seeds) act as templates on which crystals grow
- for nucleus to form rate of addition of atoms to nucleus must be faster than rate of loss
- once nucleated, growth proceeds until equilibrium is attained

Driving force to nucleate increases as we increase $\Delta T$

- _____ (eutectic, eutectoid)
- _____ (peritectic)

Small supercooling → _____ - few nuclei - ____ crystals

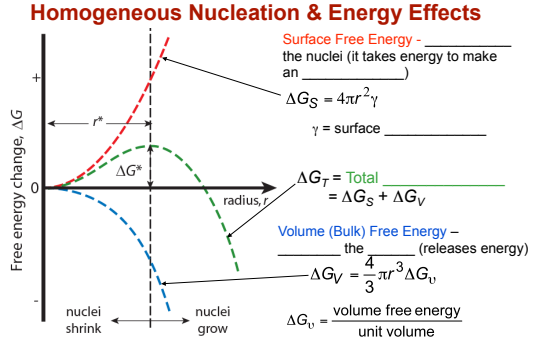
Large supercooling → _____ - many nuclei - ____ crystals



# Solidification: Nucleation Types

- Homogeneous nucleation
  - nuclei form in the bulk of liquid _____
  - requires considerable _____ (typically 80-300°C)
- _____ nucleation
  - much easier since _____ "nucleating surface" is already present—e.g., mold wall, impurities in liquid phase
  - only very slight _____ (0.1-10ºC)

## Homogeneous Nucleation & Energy Effects




Surface Free Energy - _____ the nuclei (it takes energy to make an _____)

$\Delta G_S = 4\pi r^2 \gamma$

$\gamma$ = surface _____

$\Delta G_T$ = Total _____ $= \Delta G_S + \Delta G_V$

Volume (Bulk) Free Energy – _____ the _____ (releases energy)

$\Delta G_V = \frac{4}{3}\pi r^3 \Delta G_v$

$\Delta G_v = \frac{\text{volume free energy}}{\text{unit volume}}$

$r^*$ = critical nucleus: for $r < r^*$ nuclei _____; for $r > r^*$ nuclei grow (to reduce energy)

Adapted from Fig.10.2(b), *Callister & Rethwisch 8e.*



## Solidification

$$r^* = \frac{-2\gamma T_m}{\Delta H_f \Delta T}$$

$r^*$ = critical radius
$\gamma$ = surface free energy
$T_m$ = melting temperature
$\Delta H_f$ = latent heat of _____
$\Delta T = T_m - T$ = supercooling

Note: $\Delta H_f$ and $\gamma$ are _____ dependent on $\Delta T$

$\therefore$ $r^*$ _____ as $\Delta T$ increases

For typical $\Delta T$ $r^*$ ~ 10 nm

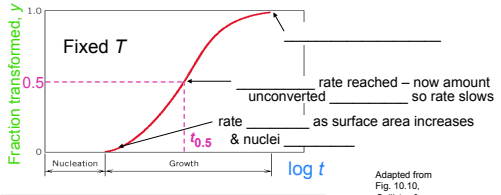


## Rate of Phase Transformations

Kinetics - study of reaction rates of phase transformations

- To determine reaction rate – measure degree of _____ as function of time (while holding temp constant)
  - How is degree of _____ measured?
    - _____ – many specimens required
    - electrical conductivity measurements – on _____ specimen
    - measure _____ of sound waves – on single specimen

## Rate of Phase Transformation




_____ rate reached – now amount unconverted _____ so rate slows

rate _____ as surface area increases & nuclei _____

Adapted from Fig. 10.10, *Callister & Rethwisch 8e.*

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

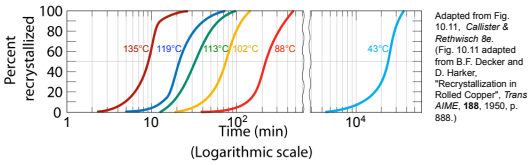
fraction transformed — time

– $k$ & $n$ are _____ specific parameters

By convention $rate = 1 / t_{0.5}$



## Temperature Dependence of Transformation Rate




Adapted from Fig. 10.11, *Callister & Rethwisch 8e.* (Fig. 10.11 adapted from B.F. Decker and D. Harker, "Recrystallization in Rolled Copper", *Trans AIME*, **188**, 1950, p. 888.)

- For the _____ of Cu, since

  $rate = 1/t_{0.5}$

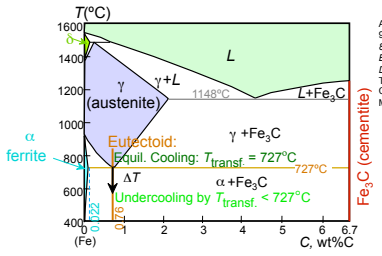
  rate _____ with _____ temperature

- Rate often so _____ that attainment of _____ state not possible!



## Transformations & Undercooling

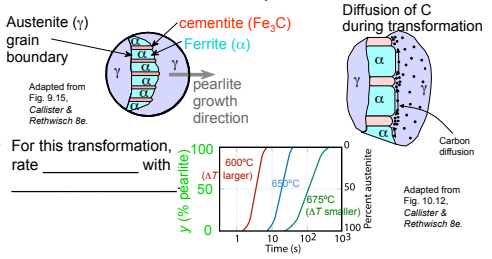
- _____ transf. (Fe-$Fe_3C$ system): $\gamma \Rightarrow \alpha + Fe_3C$
  (0.76 wt% C; 0.022 wt% C; 6.7 wt% C)
- For transf. to occur, must cool to below _____ (i.e., must "_____")




Adapted from Fig. 9.24, *Callister & Rethwisch 8e.* (Fig. 9.24 adapted from *Binary Alloy Phase Diagrams*, 2nd ed., Vol. 1, T.B. Massalski (Ed.-in-Chief), ASM International, Materials Park, OH, 1990.)

## The Fe-$Fe_3C$ Eutectoid Transformation

- Transformation of austenite to pearlite:




- For this transformation, rate _____ with _____

Coarse _____ → formed at higher temperatures – relatively _____

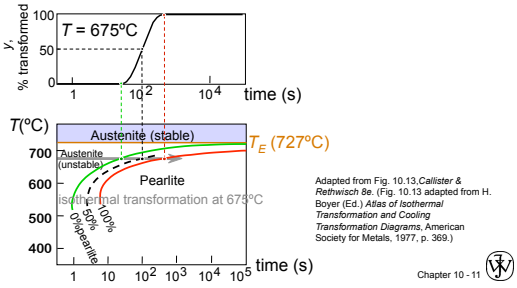
Fine _____ → formed at lower temperatures – relatively _____



## Generation of Isothermal Transformation Diagrams

Consider:

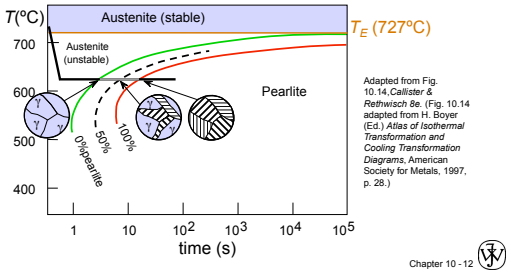
- The Fe-$Fe_3C$ system, for $C_o$ = _____ wt% C
- A transformation temperature of _____.





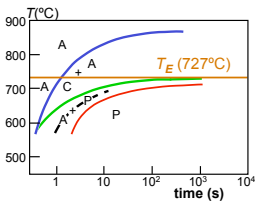

## Austenite-to-Pearlite Isothermal Transformation

- Eutectoid composition, $C_o$ = 0.76 wt% C
- Begin at $T$ > _____
- Rapidly _____
- Hold $T$ (625°C) _____ (_____ treatment)

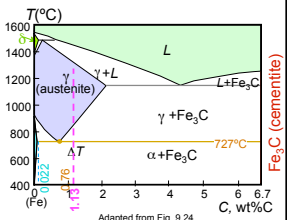


## Transformations Involving Noneutectoid Compositions

Consider $C_0$ = 1.13 wt% C




Adapted from Fig. 10.16, *Callister & Rethwisch 8e.*



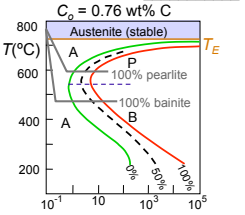

Adapted from Fig. 9.24, *Callister & Rethwisch 8e.*

Hypereutectoid composition – _____ cementite

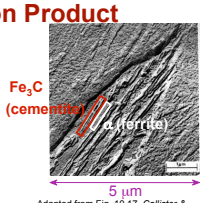


## Bainite: Another Fe-$Fe_3C$ Transformation Product

- _____:
  --elongated $Fe_3C$ _____ in α-ferrite _____
  --_____ controlled
- Isothermal Transf. _____,
  $C_o$ = 0.76 wt% C




Adapted from Fig. 10.18, *Callister & Rethwisch 8e.*

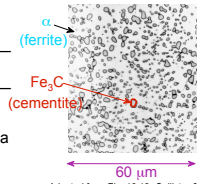



Adapted from Fig. 10.17, *Callister & Rethwisch 8e.* (Fig. 10.17 from *Metals Handbook*, 8th ed., Vol. 8, *Metallography, Structures, and Phase Diagrams*, American Society for Metals, Materials Park, OH, 1973.)



## Spheroidite: Another Microstructure for the Fe-$Fe_3C$ System

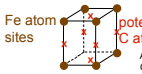
- Spheroidite:
  --$Fe_3C$ particles within _____
  --formation requires _____
  --heat _____
  just below eutectoid for long times
  --driving force – reduction of α-ferrite/$Fe_3C$ _____ area




Adapted from Fig. 10.19, *Callister & Rethwisch 8e.* (Fig. 10.19 copyright United States Steel Corporation, 1971.)

## Martensite: A Nonequilibrium Transformation Product

- _____:
  -- γ(FCC) to _____ (BCT)

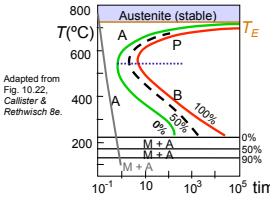



Adapted from Fig. 10.20, *Callister & Rethwisch 8e.*


Martensite needles
Austenite

Adapted from Fig. 10.21, *Callister & Rethwisch 8e.* (Fig. 10.21 courtesy United States Steel Corporation.)

- Isothermal Transf. Diagram

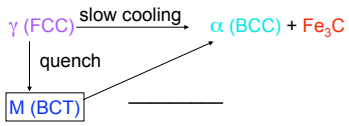



Adapted from Fig. 10.22, *Callister & Rethwisch 8e.*

- γ to _____ (M) transformation..
  -- is rapid! (_____)
  -- % transf. depends only on __ to which rapidly _____



## Martensite Formation




_____(M) – single phase
– has body centered tetragonal (BCT) crystal structure

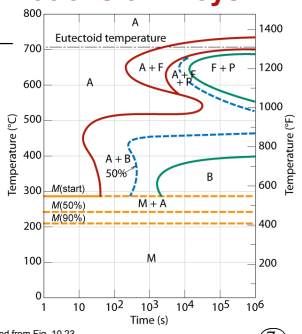
_____ transformation BCT if $C_0$ > 0.15 wt% C
BCT → few slip planes → hard, brittle



## Phase Transformations of Alloys

Effect of adding other _____
Change transition temp.

Cr, Ni, Mo, Si, Mn
retard γ → α + $Fe_3C$
reaction (and formation of _____)




Adapted from Fig. 10.23, *Callister & Rethwisch 8e.*

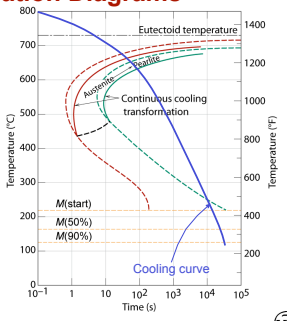
## Continuous Cooling Transformation Diagrams

Conversion of isothermal

_____

continuous cooling

_____




Adapted from Fig. 10.25, *Callister & Rethwisch 8e.*



## Isothermal Heat Treatment Example Problems

On the isothermal transformation diagram for a 0.45 wt% C, Fe-C alloy, sketch and label the time-temperature paths to produce the following microstructures:

a) 42% proeutectoid ferrite and 58% coarse pearlite

b) 50% fine pearlite and 50% bainite

c) 100% martensite

d) 50% martensite and 50% austenite



## Solution to Part (a) of Example Problem

a) 42% proeutectoid ferrite and 58% coarse pearlite

Isothermally treat at _____

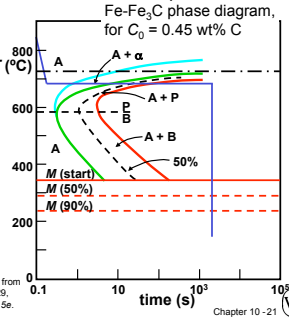
-- all _____ transforms to proeutectoid $\alpha$ and coarse pearlite.

$$W_{pearlite} = \frac{C_o - 0.022}{0.76 - 0.022}$$

_____

$W_\alpha = 1 - 0.58 =$ _____

Fe-$Fe_3C$ phase diagram, for $C_0$ = 0.45 wt% C



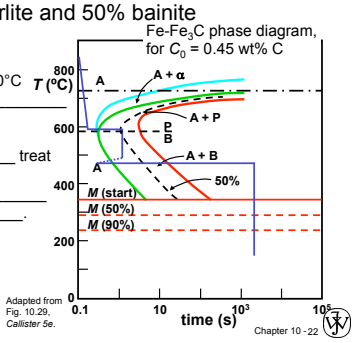

Adapted from Fig. 10.29, *Callister 5e.*

## Solution to Part (b) of Example Problem

b) 50% fine pearlite and 50% bainite

Isothermally treat at ~590°C
– _____
to fine pearlite.

Then _____ treat at ~470°C
– all remaining _____ transforms to _____.



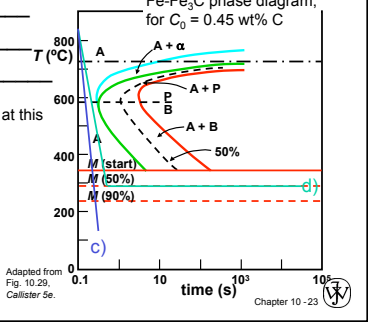

Adapted from Fig. 10.29, *Callister 5e.*



## Solutions to Parts (c) & (d) of Example Problem

c) 100% _____ – rapidly quench to _____

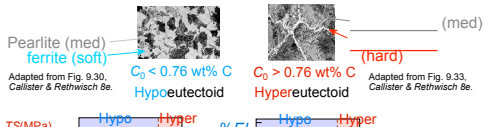
d) 50% _____ & 50% _____
-- rapidly quench to _____, hold at this temperature




Adapted from Fig. 10.29, *Callister 5e.*



## Mechanical Props: Influence of C Content

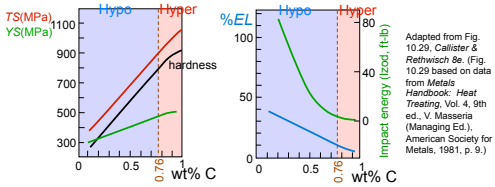



Adapted from Fig. 9.30, *Callister & Rethwisch 8e.*

$C_0$ < 0.76 wt% C
Hypoeutectoid

$C_0$ > 0.76 wt% C
Hypereutectoid

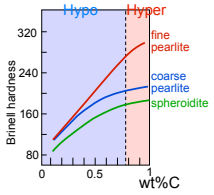
Adapted from Fig. 9.33, *Callister & Rethwisch 8e.*

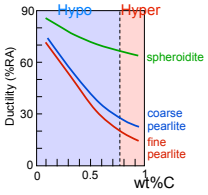



Adapted from Fig. 10.29, *Callister & Rethwisch 8e.* (Fig. 10.29 based on data from *Metals Handbook: Heat Treating*, Vol. 4, 9th ed., V. Masseria (Managing Ed.), American Society for Metals, 1981, p. 9.)

- Increase C content: *TS* and *YS* increase, *%EL* decreases

## Mechanical Props: Fine Pearlite vs. Coarse Pearlite vs. Spheroidite



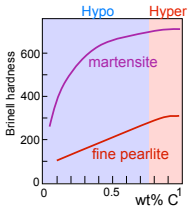




Adapted from Fig. 10.30, *Callister & Rethwisch 8e.* (Fig. 10.30 based on data from *Metals Handbook: Heat Treating*, Vol. 4, 9th ed., V. Masseria (Managing Ed.), American Society for Metals, 1981, pp. 9 and 17.)

- Hardness: _____
- %RA: _____



## Mechanical Props: Fine Pearlite vs. Martensite




Adapted from Fig. 10.32, *Callister & Rethwisch 8e.* (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.)

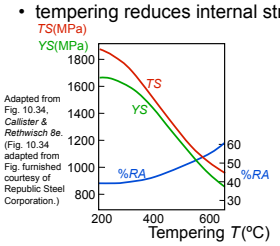
- Hardness: _____.



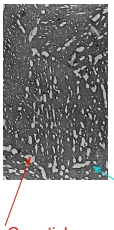
## Tempered Martensite

Heat treat martensite to form tempered martensite

- tempered martensite _____ brittle than martensite
- tempering reduces internal stresses caused by _____

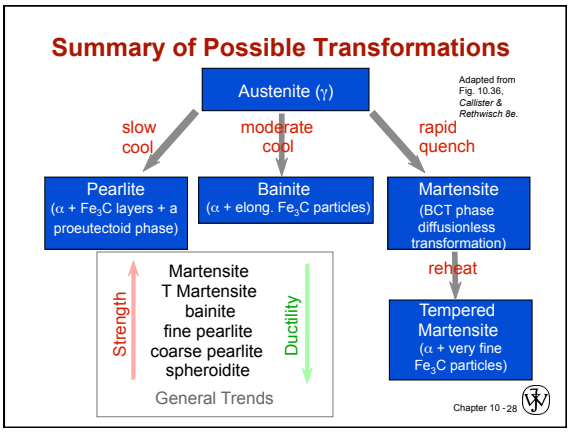



Adapted from Fig. 10.34, *Callister & Rethwisch 8e.* (Fig. 10.34 adapted from Fig. furnished courtesy of Republic Steel Corporation.)




Adapted from Fig. 10.33, *Callister & Rethwisch 8e.* (Fig. 10.33 copyright by United States Steel Corporation, 1971.)

- tempering produces extremely small $Fe_3C$ particles surrounded by $\alpha$.
- tempering _____ *TS*, *YS* but _____ %RA


Summary of Possible Transformations
Austenite (γ)
Adapted from Fig. 10.36, Callister & Rethwisch 8e.
slow cool
moderate cool
rapid quench
Pearlite (α + Fe3C layers + a proeutectoid phase)
Bainite (α + elong. Fe3C particles)
Martensite (BCT phase diffusionless transformation)
reheat
Tempered Martensite (α + very fine Fe3C particles)
Strength
Martensite
T Martensite
bainite
fine pearlite
coarse pearlite
spheroidite
Ductility
General Trends
Chapter 10 - 28