Phase Diagram (Phase Transformations)

ENT 145 Materials Engineering

Phase Transformations

- Development set of desirable mechanical characteristic for material often result from a phase transformation
- Phase transformation – an alteration in the number and/or character phases
- Transformation does not occur instantaneously, they begin with formation of small particles of new phases, which increase in size until transformation completed.
- dependence of reaction progress on time/transformation rate.
- One limitation of phase diagrams is their ability to indicate the time period required for attainment of equilibrium
- Phase transformation divided into 2 stages nucleation and growth
- once nucleated, growth proceeds until equilibrium is attained

Phase Transformations

- **Phase transformations** (change of the microstructure) can be divided into three categories:
  - **Diffusion-dependent with no change in phase composition or number of phases present** (e.g. melting, solidification of pure metal, allotropic transformations, recrystallization, etc.)
  - **Diffusion-dependent with changes in phase compositions and/or number of phases** (e.g. eutectic or eutectoid transformations)
  - **Diffusionless phase transformation** - by cooperative small displacements of all atoms in structure, e.g. martensitic transformation.
- Phase transformations do not occur instantaneously.
- Diffusion-dependent phase transformations can be rather slow and the final structure often depend on the rate of cooling/heating.

We need to consider the time dependence or kinetics of the phase transformations.

Phase Transformations

- Phase transformations involve change in structure and (for multi-phase systems) composition ⇒ rearrangement and redistribution of atoms via diffusion is required.
- The process of phase transformation involves:
  - **Nucleation** of the new phase(s) - formation of stable small particles (nuclei) of the new phase(s). Nuclei are often formed at grain boundaries and other defects.
  - **Growth** of the new phase(s) at the expense of the original phase(s).

once nucleated, growth proceeds until equilibrium is attained

Driving force to nucleate increases as we increase ΔT
- supercooling (eutectic, eutectoid)
- superheating (peritectic)

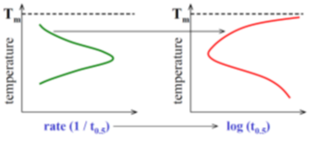
Small supercooling → slow nucleation rate - few nuclei - large crystals
Large supercooling → rapid nucleation rate - many nuclei - small crystals

Rate of Phase Transformation

To quantitatively describe the rate of a phase transformation, it can be defined as reciprocal of time for transformation to proceed halfway to completion:

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

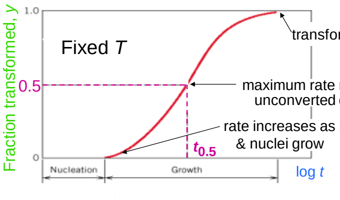
Plotting the transformation time vs temperature results in a characteristic C-shaped curves:



The analysis performed above for solidification can also be extended to other phase transformations, e.g. solid-state phase transformations.

Rate of Phase Transformation

The time dependence of solid-state phase transformations at a fixed temperature is often described in terms of the time dependence of the **fraction of transformation (*y*)**:



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

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

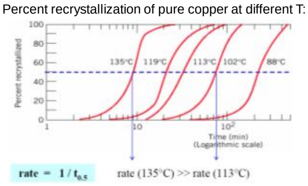
fraction transformed — time

– k & n are transformation specific parameters

Temperature Dependence of Transformation Rate

Temperature has a strong effect on the kinetics of the phase transformation and, therefore, on the rate of the phase transformation.

Percent recrystallization of pure copper at different T:

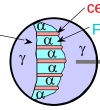


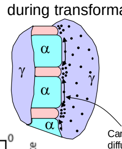
- ❑ For the recrystallization of Cu, since
  $rate = 1/t_{0.5}$
  rate increases with increasing temperature

- ❑ **Rate often so slow that attainment of equilibrium state not possible!**

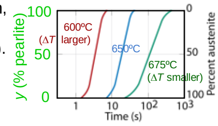
The Fe-Fe_3C Eutectoid Transformation

- Transformation of austenite to pearlite:





- For this transformation, rate increases with [$T_{eutectoid}$ – T] (i.e., ΔT).



Adapted from Fig. 10.12, Callister & Rethwisch 8e.

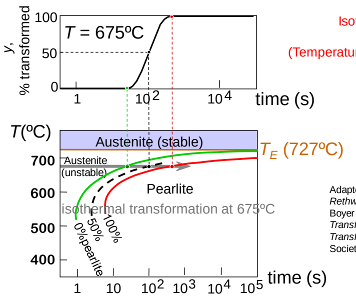
Coarse pearlite → formed at higher temperatures – relatively soft

Fine pearlite → formed at lower temperatures – relatively hard

Generation of Isothermal Transformation Diagrams (TTT Diagram)

Consider:

- The Fe-Fe_3C system, for C_0 = 0.76 wt% C
- A transformation temperature of 675ºC.

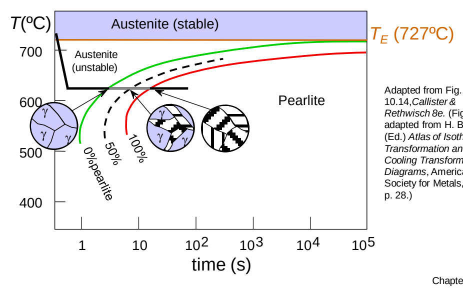


Isothermal Transformation (or TTT) Diagrams (Temperature, Time, and % Transformation)

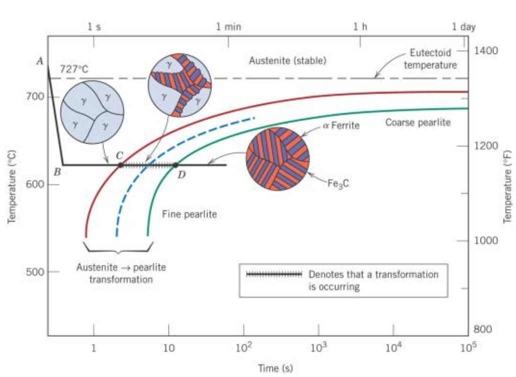
Adapted from Fig. 10.13, *Callister & Rethwisch 8e.* (Fig. 10.13 adapted from H. Boyer (Ed.) *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, 1977, p. 369.)

Austenite-to-Pearlite Isothermal Transformation

- Eutectoid composition, C_0 = 0.76 wt% C
- Begin at T > 727ºC
- Rapidly cool to 625ºC
- Hold T (625ºC) constant (isothermal treatment)



Adapted from Fig. 10.14, *Callister & Rethwisch 8e.* (Fig. 10.14 adapted from H. Boyer (Ed.) *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, 1997, p. 28.)



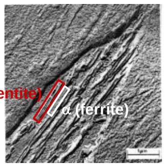
- ❑ The thickness of the ferrite and cementite layers in pearlite is ~ 8:1.
- ❑ The absolute layer thickness depends on the temperature of the transformation.
- ❑ The higher the temperature, the thicker the layers.

Coarse Pearlite

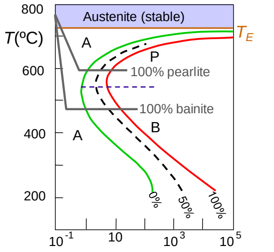
Fine Pearlite

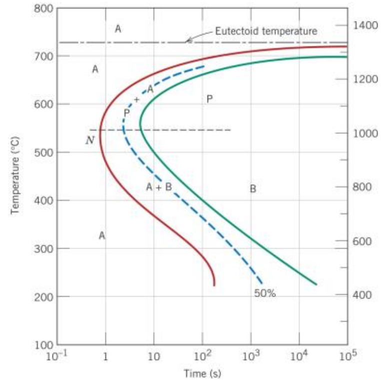
Bainite: Another Fe-Fe_3C Transformation Product

- Bainite:
  - -- elongated Fe_3C particles in α-ferrite matrix
  - -- diffusion controlled
- Isothermal Transf. Diagram, C_0 = 0.76 wt% C



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



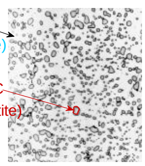


Isothermal transformation diagram iron-carbon alloy eutectoid composition

Austenite-to-Pearlite(A-P)
Austenite-to-Bainite (A-B)

Spheroidite: Another Microstructure for the Fe-Fe_3C System

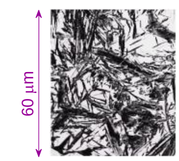
- Spheroidite:
  - -- Fe3C particles within an α-ferrite matrix
  - -- formation requires diffusion
  - -- heat bainite or pearlite at temperature just below eutectoid for long times
  - -- Ex. 700C for 18-24h
  - -- driving force – reduction of α-ferrite/Fe_3C interfacial area



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

Martensite: A Nonequilibrium Transformation Product

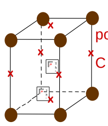
- iron-carbon aloy are rapidly cooled to a relatively low temperature
- diffusionless transformation- martensitic transformation occur when the quenching rate is rapid enough to prevent carbon diffusion.
- any diffusion will result in the formation of ferrite and cementite
- martensitic tranformation occur instantaneously- grains nucleate and grow at a very rapid rate- velocity of sound
- platelike or needlelike appearance

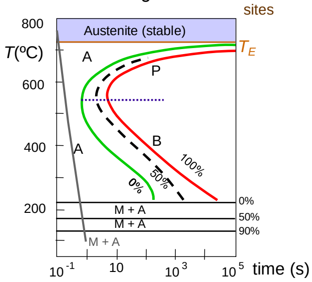


Martensite needles
Austenite

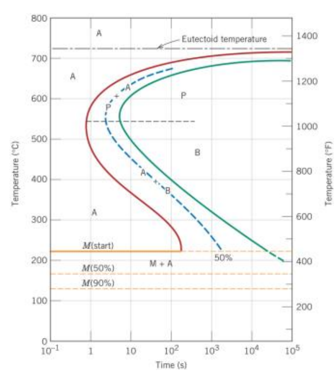
Martensite: A Nonequilibrium Transformation Product

- Martensite:
  - -- γ(FCC) to Martensite (BCT)
- Isothermal Transf. Diagram





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

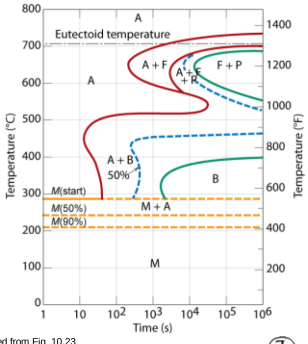


Phase Transformations of Alloys

Effect of adding other elements
Change transition temp.

Cr, Ni, Mo, Si, Mn

retard $\gamma \rightarrow \alpha + Fe_3C$ reaction (and formation of pearlite, bainite)



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

Continuous Cooling Transformation Diagrams

-- TTT Diagram though give very useful information, they are of less practical importance since an alloy has to be cooled rapidly and then kept at a temperature to allow for respective transformation to take place.

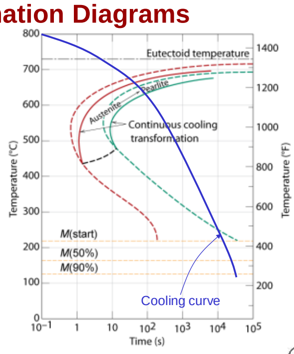
-- Usually material are cooled continuously, thus CCT diagrams are appropriate.

-- For continuous cooling, the time required for a reaction to begin and end delayed, thus the isothermal curves are shifted to longer times and lower temperatures.

-- Main difference between TTT and CCT diagrams: for iron-carbon of eutectoid composition, no space for bainite in CCT diagram as continuous cooling always result in formation of pearlite.

Continuous Cooling Transformation Diagrams

Conversion of isothermal transformation diagram to continuous cooling transformation diagram



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

Example Problem: Isothermal Heat Treatment

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) 50% fine pearlite and 50% bainite

b) 100% martensite

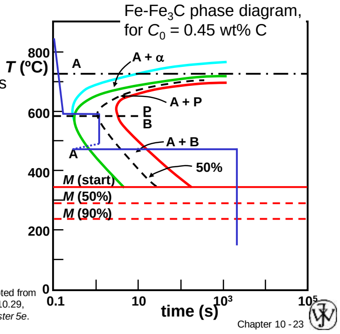
c) 50% martensite and 50% austenite

Solution to Part (b)

a) 50% fine pearlite and 50% bainite

Isothermally treat at ~ 590ºC
– 50% of austenite transforms to fine pearlite.

Then isothermally treat at ~ 470ºC
– all remaining austenite transforms to bainite.



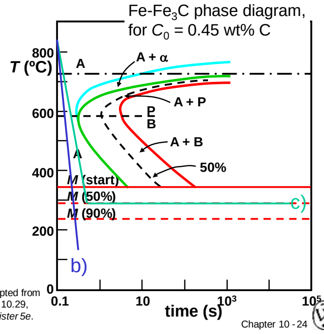
Adapted from Fig. 10.29, *Callister 5e.*

Solutions to Parts (b) & (c)

b) 100% martensite – rapidly quench to room temperature

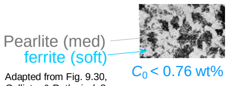
c) 50% martensite & 50% austenite

-- rapidly quench to ~ 290ºC, hold at this temperature



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

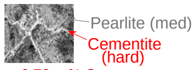
Mechanical Props: Influence of C Content



C_0 < 0.76 wt% C

Hypoeutectoid

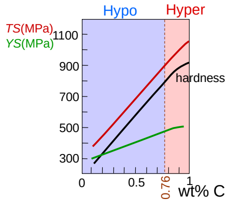
Adapted from Fig. 9.30, *Callister & Rethwisch 8e.*

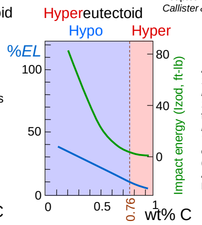


C_0 > 0.76 wt% C

Hypereutectoid

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

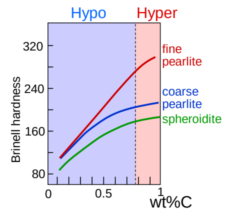


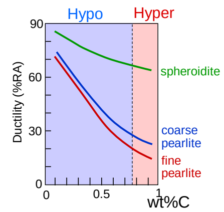


Adapted from Fig. 10.29, *Callister & Rethwisch 8e.* (Fig. 10.29 based on data from *Metals Handbook: Heat Treating*, Vol. 4, 9th ed., V. Masseria (Managing Ed.), American Society for Metals, 1981, p. 9.)

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

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

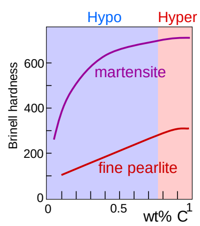




- Hardness: fine > coarse > spheroidite
- %RA: fine < coarse < spheroidite

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.)

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: fine pearlite << martensite.

Tempered Martensite

-- apply a heat treatment process known as tempering on martensite to enhance ductility and toughness of martensite

-- tempering – heating a martensitic steel to a temperature below eutectoid for a specified time

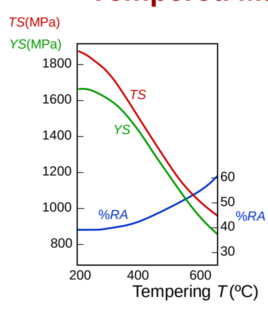
-- tempering reduces internal stresses caused by quenching

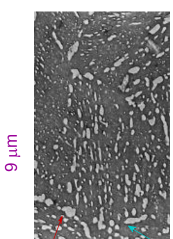
-- normally, tempering is carried out at temperatures between 250-650 degree C.

-- optimum for internal stresses relieved at 200C for 1hour

-- nearly hard and strong as martensite, but with substantially enhanced ductility and toughness

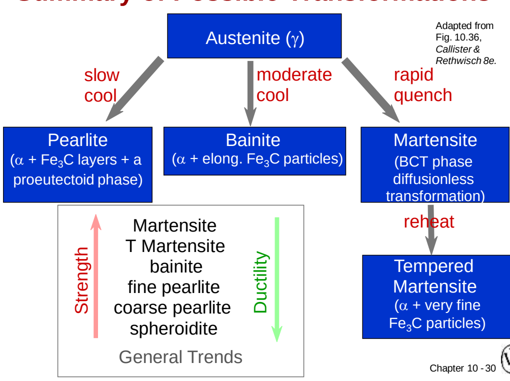
Tempered Martensite





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

Summary of Possible Transformations



Adapted from Fig. 10.36, *Callister & Rethwisch 8e.*

Homework

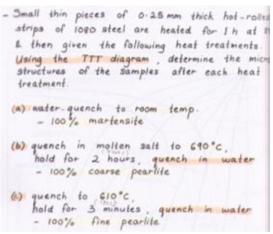
Using the isothermal transformation diagram for an iron–carbon alloy of eutectoid composition (Refer figure below), specify the nature of the final microstructure (in terms of microconstituents present and approximate percentages of each) of a small specimen that has been subjected to the following time–temperature treatments. In each case assume that the specimen begins at 760°C (1033 K) and that it has been held at this temperature long enough to have achieved a complete and homogeneous austenitic structure.

a)Cool rapidly to 700°C (973 K), hold for 10^4 s, then quench to room temperature.
b)Reheat the specimen in part (a) to 700°C (973 K) for 20 h.
c)Rapidly cool to 600°C (873 K), hold for 4 s, rapidly cool to 448°C (721 K), hold for 10 s, then quench to room temperature.
d)Cool rapidly to 398°C (671 K), hold for 2 s, then quench to room temperature.
e)Cool rapidly to 398°C (671 K), hold for 20 s, then quench to room temperature.
f)Cool rapidly to 398°C (671 K), hold for 200 s, then quench to room temperature.
g)Rapidly cool to 575°C (848 K), hold for 20 s, rapidly cool to 350°C (623 K), hold for 100 s, then quench to room temperature.
h)Rapidly cool to 250°C (523 K), hold for 100 s, then quench to room temperature in water. Reheat to 315°C (588 K) for 1 h and slowly cool to room temperature.

HOMEWORK

1) Describe characteristics of (a) an alloy (b) pearlite, (c) austenite (d) martensite , (e) cementite, (f) spherodite and (g) tempered martensite.
2) Choose one engineering application that its material consist at least ONE of above microstructures. Explain details of the application with respect to its fabrication method, mechanical properties and heat treatment procedure. You may review any available literature in the library or internet.

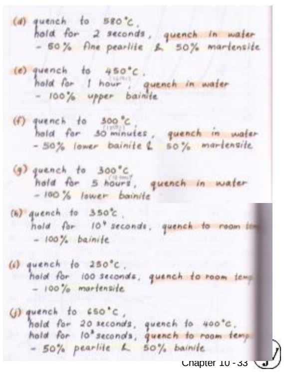
ASSIGNMENT


- Small thin pieces of 0.25 mm thick hot-rolled strips of 1080 steel are heated for 1 h at ... & then given the following heat treatments. Using the TTT diagram, determine the micro-structures of the samples after each heat treatment.

(a) water-quench to room temp.
- 100% martensite

(b) quench in molten salt to 690°C, hold for 2 hours, quench in water
- 100% coarse pearlite

(c) quench to 610°C, hold for 3 minutes, quench in water
- 100% fine pearlite


(d) quench to 580°C, hold for 2 seconds, quench in water
- 50% fine pearlite & 50% martensite

(e) quench to 450°C, hold for 1 hour, quench in water
- 100% upper bainite

(f) quench to 300°C, hold for 30 minutes, quench in water
- 50% lower bainite & 50% martensite

(g) quench to 300°C, hold for 5 hours, quench in water
- 100% lower bainite

(h) quench to 350°C, hold for 10^4 seconds, quench to room temp
- 100% bainite

(i) quench to 250°C, hold for 100 seconds, quench to room temp
- 100% martensite

(j) quench to 650°C, hold for 20 seconds, quench to 400°C, hold for 10^3 seconds, quench to room temp
- 50% pearlite & 50% bainite

- ✓ **In-class assignment.**
- ✓ **Individual assessment.**
- ✓ **Submit by today, at the end of tutorial session.**
- ✓ **Late submission will not be entertained!!!**