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.
- Once nucleated, growth proceeds until equilibrium is attained

Phase Transformations

- Phase transformations involve change in structure and (supercooling)
- Diffusionless
- The process of phase transformation involves:
  - Nucleation and growth
  - Transformation does not occur instantaneously, they begin with formation of small particles of new phases, which increase in size until transformation completed.

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:

\[ \text{rate} = \frac{1}{t_{1/2}} \]

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.
Chapter 10 - 7

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.

Rate often so slow that attainment of equilibrium state not possible

For the recrystallization of Cu, since rate = \( \frac{1}{t^{0.5}} \), rate increases with increasing temperature

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:

Chapter 10 - 8

The Fe-Fe₃C Eutectoid Transformation

Coarse pearlite → formed at higher temperatures – relatively soft
Fine pearlite → formed at lower temperatures – relatively hard

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

Adapted from Fig. 9.15, Callister & Rethwisch 8e.

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

Generation of Isothermal Transformation Diagrams (TTT Diagram)

Consider:
- The Fe-Fe₃C system, for \( C_0 = 0.76 \text{ wt}\% C \)
- A transformation temperature of 675°C

Austenite (stable)

Austenite (unstable)

Pearlite

Austenite transformation at 675°C

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.)

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.)

Austenite-to-Pearlite Isothermal Transformation

- Eutectoid composition, \( C_0 = 0.76 \text{ wt}\% C \)
- Begin at \( T > 727°C \)
- Rapidly cool to 625°C
- Hold \( T (625°C) \) 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.

Chapter 10 - 9

Chapter 10 - 10

The Fe-Fe₃C Eutectoid Transformation

Transformation of austenite to pearlite:

Adapted from Fig. 9.15, Callister & Rethwisch 8e.

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

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.)

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Austenite transformation at 675°C

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Bainite: Another Fe-Fe₃C Transformation Product

- Bainite:
  - elongated Fe₃C particles in ω-ferrite matrix
  - diffusion controlled
- Isothermal Transf. Diagram,
  \( C_0 = 0.76 \) wt% C

\( \text{Fe}_3\text{C} \) (cementite)

Spheroidite: Another Microstructure for the Fe-Fe₃C System

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

Martensite: A Nonequilibrium Transformation Product

- iron-carbon alloy 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 transformation occur instantaneously- grains nucleate and grow at a very rapid rate- velocity of sound
- platelike or needlelike appearance

Martensite needles

Martensite: A Nonequilibrium Transformation Product

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

Fe atom sites

C atom sites
Phase Transformations of Alloys

Effect of adding other elements
Change transition temp.
Cr, Ni, Mo, Si, Mn
retard γ → α + Fe₃C reaction (and formation of pearlite, bainite)

Continuous Cooling Transformation Diagrams

Continuous Cooling Transformation Diagrams
Conversion of isothermal transformation diagram to continuous cooling transformation diagram

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)

Fe-Fe₃C phase diagram, for C₀ = 0.45 wt% C

Solution to Parts (b) & (c)

Fe-Fe₃C phase diagram, for C₀ = 0.45 wt% C

b) 100% martensite – rapidly quench to room temperature
c) 50% martensite & 50% austenite – rapidly quench to ~290°C, hold at this temperature
Mechanical Props: Influence of C Content

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

C < 0.76 wt% C
- Hypo-eutectoid
- Ferrite (soft)
- Pearlite (med)

C > 0.76 wt% C
- Hyper-eutectoid
- Cementite (hard)
- Spherical (hard)

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

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.

Mechanical Props: Fine Pearlite vs. Martensite

- Hardness: fine pearlite << martensite

Adapted from Fig. 10.32, Callister & Rethwisch 8e.

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 the 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 1 hour
- Nearly hard and strong as martensite, but with substantially enhanced ductility and toughness

Summary of Possible Transformations

<table>
<thead>
<tr>
<th>Austenite (γ)</th>
<th>Slow cool</th>
<th>Moderate cool</th>
<th>Rapid quench</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearlite (α + Fe₃C layers + a proeutectoid phase)</td>
<td>Martensite (BCT phase transformation)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bainite (α + elong. Fe₃C particles)</td>
<td>Tempered Martensite (α + very fine Fe₃C particles)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Adapted from Fig. 10.36, Callister & Rethwisch 8e.
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 4 s, rapidly cool to 448°C (721 K), hold for 10 s, then quench to room temperature.

e) Cool rapidly to 398°C (671 K), hold for 20 s, then quench to room temperature.

f) Rapidly cool 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. (Note: This treatment is not mentioned in the text, but it is possible that it is intended to be a part of the series.)

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.

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**ASSIGNMENT**

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

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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.