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/supercooling dependence of reaction progress on time/transformation rate.
- Phase diagrams of compositions - are often reciprocal

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):

Fraction transformed

Maximum rate reached – now amount unconverted decreases so rate slows

Rate increases as surface area increases & nuclei grow

Avrami equation => \( y = 1 - \exp(-k t^n) \)

- \( k \) & \( n \) are transformation specific parameters

Driving force to nucleate increases as we increase \( \Delta T \)
- 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

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

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

\[ \text{rate} = \frac{1}{n_s} \]

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.
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.

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

Rate often so slow that attainment of equilibrium state not possible.

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

- Transformation of austenite to pearlite:
  - Eutectoid composition, $C_0 = 0.76$ wt% C
  - Begin at $T > 727^\circ$C
  - Rapidly cool to 625ºC
  - Hold $T (625^\circ$C) constant (isothermal treatment)

The Fe-Fe$_3$C Eutectoid Transformation

- Transformation of austenite to pearlite:
  - Austenite (stable)
  - Austenite (unstable)
  - Pearlite

Coarse pearlite $\rightarrow$ formed at higher temperatures $\rightarrow$ relatively soft

Fine pearlite $\rightarrow$ formed at lower temperatures $\rightarrow$ relatively hard

Generation of Isothermal Transformation Diagrams (TTT Diagram)

Consider:
- The Fe-Fe$_3$C system, for $C_0 = 0.76$ wt% C
- A transformation temperature of 675ºC.

Austenite-to-Pearlite Isothermal Transformation

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

The thickness of the ferrite and cementite layers in pearlite is $\approx 8:1$.

The absolute layer thickness depends on the temperature of the transformation.

The higher the temperature, the thicker the layers.
Bainite: Another Fe-Fe₃C Transformation Product

- Bainite:
  - elongated Fe₃C particles in α-ferrite matrix
  - diffusion controlled
- Isothermal Transf. Diagram, C₀ = 0.76 wt% C

Isothermal transformation diagram iron-carbon alloy eutectoid composition
Austenite to Pearlite (A-P) Austenite to Bainite (A-B)

Spheroidite: Another Microstructure for the Fe-Fe₃C 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. 700°C for 18-24h
  - driving force – reduction of α-ferrite/Fe₃C interfacial area

Martensite: A Nonequilibrium Transformation Product

- iron-carbon alloy 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
- platelet or needlelike appearance

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)

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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 euctectoid composition, no space for bainite in CCT diagram as continuous cooling always result in formation of pearlite.

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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

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Solution to Part (b)

a) 50% fine pearlite and 50% bainite

Isothermally treat at ~ 590°C
-- 50% of austenite transforms to fine pearlite.
Then isothermally treat at ~ 470°C
-- all remaining austenite transforms to bainite.

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Solutions to Parts (b) & (c)

b) 100% martensite – rapidly quench to room temperature

c) 50% martensite & 50% austenite
-- rapidly quench to ~ 200°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
- Hypoeutectoid
- Pearlite (med)
- Ferrite (soft)

C > 0.76 wt% C
- Hypereutectoid
- Pearlite (med) + Cementite

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 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

Tempered Martensite

- tempered produces extremely small Fe₃C particles surrounded by a.
- tempered decreases TS, YS but increases %RA

Summary of Possible Transformations

Austenite (γ) → Pearlite (α + Fe₃C layers + a proeutectoid phase) → Bainite (α + elongated Fe₃C particles) → Martensite (BCT phase transformation) → Tempered Martensite (α + very fine Fe₃C particles)

General Trends
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 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 660°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 (721 K), hold for 2 s, then quench to room temperature.

e) Cool rapidly to 398°C (721 K), hold for 20 s, then quench to room temperature.

f) Cool rapidly to 398°C (721 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) spheroidite 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

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