Fe-C Phase Diagram

Pure Iron

- Upon heating pure Iron experiences two changes in crystal structure.
- At room temperature it exists as ferrite, or \( \alpha \) iron.
  - BCC crystal structure
  - mostly iron with a little carbon
  - relatively soft
- When we heat it to 912°C it experiences a polymorphic transformation to austenite, or \( \gamma \) iron
  - FCC crystal structure
  - Unstable at room temp.
  - Can accommodate more carbon than ferrite
- At 1394°C austenite reverts back to a BCC phase called \( \delta \) ferrite.
Fe-Fe$_3$C Phase Diagram

- Only part of the phase diagram is shown.
- The left axis is pure iron.
- On the right the phase diagram only extends to 6.70 wt% C.
- At this concentration the intermediate compound iron carbide, or cementite ($Fe_3C$) is formed.
- This is sufficient to describe all of the steels and cast irons used today.

Development of Microstructures in Iron-Carbon Alloys

- Various microstructures can be produced in steel alloys depending on
  - carbon content
  - heat treatment
- Equilibrium (slow) cooling from the γ region through the eutectoid composition of 0.76 wt% C

\[
\gamma \Rightarrow \alpha + Fe_3C \quad \text{(Pearlite)}
\]

- \% α and $Fe_3C$ in eutectoid pearlite

\[
W_\alpha = \frac{6.7 - 0.76}{6.7 - 0.022} \times 100 = 89%
\]

\[
W_{Fe_3C} = \frac{0.76 - 0.022}{6.7 - 0.022} \times 100 = 11%
\]
Formation of Pearlite

- Schematic representation of the formation of pearlite from austenite
  - direction of arrows indicates carbon diffusion
- Micrograph of eutectoid steel, showing pearlite microstructure.
  - α ferrite (light)
  - Fe₃C (dark)

Hypo-eutectoid Composition (wt% C <0.76)

- Composition 0.002 and 0.76 wt% C
- Upon cooling enter a two-phase region
  \[ \gamma \Rightarrow \alpha + \gamma \]
- Below 727°C the remaining austenite transforms to pearlite
  \[ \gamma \Rightarrow \alpha + Fe₃C \]
- Final structure is a mixture of
  - Pro-eutectoid ferrite
  - Pearlite
Hypo-eutectoid Composition (0.38 wt% C)

White regions: Proeutectoid Ferrite

Dark regions: Pearlite Close-spaced layers Unresolved at this magnification

Pearlite wider-spaced layers 91 μm

Computing the relative amounts of proeutectoid α and pearlite

• Similar to previous lecture.
• Use the Lever Rule in conjunction with a tie line
• For hypoeutectic composition $C'_0$, fractions of pro-eutectic $\alpha$, and pearlite are:
  
  $W_\alpha = \frac{U}{T + U}$
  
  $W_p = \frac{T}{T + U}$

• $\alpha$ (total) and Fe$_3$C
  
  $W_\alpha = \frac{U + V + X}{T + U + V + X}$
  
  $W_{Fe_3C} = \frac{T}{T + U + V + X}$
Computing the relative amounts of proeutectoid $\alpha$ and pearlite

- For hypereutectic composition $C'_1$
  
  \[ W_{Fe_3C} = \frac{V}{V + X} \]
  \[ W_\alpha = \frac{X}{V + X} \]

- $\alpha$ (total) and Fe$_3$C
  \[ W_\alpha = \frac{X}{T + U + V + X} \]
  \[ W_{Fe_3C} = \frac{T + U + V}{T + U + V + X} \]

Hyper-eutectoid Composition (wt% C >0.76)

- Composition between 0.76 and 2.14 wt% C
- Upon cooling enter a two-phase region
  \[ \gamma \Rightarrow \gamma + Fe_3C \]
- The pro-eutectoid cementite phase has begun to form along the $\gamma$ grain boundaries
- Final structure is a mixture of
  - Pro-eutectoid cementite
  - Pearlite
Hyper-eutectoid Composition (1.40 wt% C)

Mechanical Properties of Steels

- The mechanical properties of steel are largely dictated by the phase transformations they undergo upon cooling.
- If we heat steel to the **single phase austenite region** and vary the cooling rate we can control the microstructure.
- Understanding phase transformations of metallic alloys
  - allows us to design a heat treatment for a specific alloy
  - that will yield the desired room temperature mechanical properties
Example: Railway Rails

- Eutectoid composition of 0.76 wt%C
- 100% Pearlite structure
- Pearlite is a natural ‘composite’
  - Hard and Brittle Fe₃C plates
  - Soft and Ductile ferrite plates
- The strength of Pearlite is dictated by its interlaminar spacing, \( S (\mu m) \)
  \[
  \sigma_f = 140 + 46.4S^{-1}
  \]

Pearlite

Coarse Pearlite     Fine Pearlite
Isothermal Transformation Diagrams

- The rate of transformation of the austenite to pearlite is dependent on temperature.
- This temperature dependence can be plotted as % transformation vs. log. time.
- Data was collected for each curve, after rapid cooling of 100% austenite to the temperature indicated.
  - Temperature was then kept constant throughout the course of the reaction.

Eutectoid composition (0.76 wt% C)
Cool rapidly from 100% austenite through eutectoid isotherm (727 °C) to 600, 650, 675°C

- More convenient to represent time-temperature dependence.
  - Isothermal transformation diagram.
  - Generated from the % transformation-versus-log. times measurements.
  - Note the eutectoid temperature (727°C).
- Many tests conducted to construct curves.
Spheroidite

- Hold steel at high temperature
  - Below 727 °C
  - for a sufficiently long time
  - the Fe₃C (cementite) plates spheroidize
  - the continuous phase is α ferrite
- Large drop in strength occurs
- But ductility is greatly increased
Formation of Martensite

- Non-Equilibrium Cooling
- Carbon must diffuse (move) in order to form pearlite
  - low C in α-Fe
  - high C in Fe₃C
- Diffusion takes time + temperature
- If the sample is “quenched” (plunged into water)
  - no time for diffusion
  - pearlite cannot form
- A supersaturated and unstable structure is formed.
  - Lattice gets “stuck” between FCC and BCC
  - i.e. we get Body Centred Tetragonal (BCT)
    structure or in terms of lattice parameters, \( a \neq c \)

Characteristics of Martensite Transformation

- Occurs by a non-diffusional process
- Transformation occurs extremely fast, i.e. at the speed of sound
- Transformation occurs at temperatures well below eutectoid temperature
- Martensite is very hard (i.e. high \( \sigma_y \)) but is completely brittle
- Not useful as an engineering material
- Must be “tempered”
Martensite

- Quench
  - Needle shaped
  - White areas austenite
    - quenched too fast
- Tempered
  - 564°C
  - small particles cementite
  - matrix is α ferrite

Effect of Carbon Content on Hardness

Brinell Hardness 0 - 320
Brinell Hardness 0 - 750
Effect of Carbon Content on Yield and Tensile Strength