**Martensite**

- Athermal transformation
- Massive martensite
- Plate martensite
Body centered tetragonal (BCT) structure.

“$M_s$” stands for “Martensite Start Temperature” and “$M_f$” stands for “Martensite Finished Temperature”.

Due to the fast cooling, diffusion of carbon is restricted. To make room for the carbon atoms, the lattice stretches along one crystal direction.

Martensite is a metastable phase.
Martensite is a supersaturated solution of carbon in iron. Due to the high lattice distortion, martensite has high residual stresses. The high lattice distortion induces high hardness and strength to the steel. However, ductility is loss (martensite is too brittle) and a post heat treatment is necessary.
Heat treatment

Examples

(a) rapidly cool to $350^\circ\text{C}$; hold $10^4\text{s}$ and then quench to room temp.

**100% bainite**

(b) rapidly cool to $250^\circ\text{C}$; hold $100\text{s}$ and then quench to room temp.

**100% martensite**

(c) rapidly cool to $650^\circ\text{C}$; hold $20\text{s}$ and rapidly cool to $400^\circ\text{C}$, hold $103\text{s}$, and then quench to room temp.

**50% pearlite + 50% bainite**
Austenite

- Slow cooling
  - Pearlite ($\alpha + Fe_3C$) + a proeutectoid phase
- Moderate cooling
  - Bainite ($\alpha + Fe_3C$ phases)
- Rapid quench
  - Martensite (BCT phase)

Diffusionless process

Body-centered tetragonal

Reheat

Tempered martensite ($\alpha + Fe_3C$ phases)

Temper embrittlement: reduction of toughness after tempering
Continuous Cooling Transformation + cooling curve
Control of final structures

Figure 10.19
Continuous cooling transformation diagram for a eutectoid iron–carbon alloy and superimposed cooling curves, demonstrating the dependence of the final microstructure on the transformations that occur during cooling.
Figure 10.20
Continuous cooling transformation diagram for an alloy steel (type 4340) and several superimposed cooling curves demonstrating dependency of the final microstructure of this alloy on the transformations that occur during cooling.
Common Industrial Heat Treatments

- Annealing (slow cooling from austenitizing temperature. Product: coarse pearlite)

- Normalizing (air cooling from austenitizing temperature. Product: fine pearlite)

- Quench & Temper. Quench (fast – water or oil – cooling from austenitizing temperature. Product: martensite). Tempering (heating to $T < A_1$ to increase ductility of quenched steels)

- Martempering. (Quench to $T$ above $M_s$ and soak until all the steel section is at that temperature, then quench to ambient temperature. Product: Martensite)

- Austempering. (Quench to $T$ above $M_s$ and soak until phase transformation takes place. Product: Bainite)
Annealing

Stages of annealing:

- Heating to required temperature
- Holding ("soaking") at constant temperature
- Cooling

The time at the high temperature (soaking time) is long enough to allow the desired transformation to occur. Cooling is done slowly to avoid warping/cracking of due to the thermal gradients and thermo-elastic stresses within the or even cracking the metal piece.
**Purposes of annealing:**

- Relieve internal stresses
- Increase ductility, toughness, softness
- Produce specific microstructure

**Examples of heat treatment**

**Process Annealing** - effects of work-hardening (recovery and recrystallization) and increase ductility. Heating is limited to avoid excessive grain growth and oxidation.

**Stress Relief Annealing** — minimizes stresses due to plastic deformation during machining

- Nonuniform cooling
- Phase transformations between phases with different densities

Annealing temperatures are relatively low so that useful effects of cold working are not eliminated.
• **Lower critical temperature** $A_1$ below which austenite does not exist
• **Upper critical temperature** lines, $A_3$ and $A_{cm}$ above which all material is austenite
• **Austenitizing** – complete transformation to austenite

**Full annealing:** austenizing and slow cooling (several hours). Produces coarse pearlite (and possible proeutectoid phase) that is relatively soft and ductile. It is used to soften pieces which have been hardened by plastic deformation, and which need to undergo subsequent machining/forming.

Temperatures for full annealing:

- Hypoeutectoid steel: $A_3 + 50^\circ$C
- Hypereutectoid steel: $A_{1,3} + 50^\circ$C
Normalizing

Annealing heat treatment just above the upper critical temperature to reduce grain sizes (of pearlite and proeutectoid phase) and make more uniform size distributions. The interlamellar distance of pearlite decreases as the cooling rate increases.

- Slow cooling (annealing – furnace cooling) – coarse pearlite – interlamellar spacing of 4.5μm – hardness of 200BHN
- Medium to slow cooling (normalizing – still air cooling) – normal pearlite – interlamellar spacing of 3.0μm – hardness of 220BHN
- Medium to Fast (normalizing – forced air cooling) – fine pearlite – interlamellar spacing of 2.0μm – hardness of 300BHN
Normalizing temperatures:
Hypoeutectoid steel: \( A_3 + 50^\circ C \)
Hypereutectoid steel: \( A_{cm} + 50^\circ C \)
Spheroidizing: prolonged heating just below the eutectoid temperature, which results in the soft spheroidite structure. This achieves maximum softness needed in subsequent forming operations.
Hardness and ductility
Quenching

The most common method to harden a steel.

It consists of heating to the austenizing temperature (hypoeutectoid steel) and cooling fast enough to avoid the formation of ferrite, pearlite or bainite, to obtain pure martensite.

Martensite (α’) has a distorted BCT structure. It is the hardest of the structures studied. The higher hardness is obtained at 100% martensite.

Martensite hardness depends solely of the carbon content of the steel. The higher the carbon content, the higher the hardness.

Martensite is very brittle and can not be used directly after quench for any application.

Martensite brittleness can be reduced by applying a post-heat treatment known as - tempering.
Cooling depends on the geometry and mass of the component. External surfaces are cooled faster than the inner core of the component.
Tempering of Martensitic Steels

- Martensite is too brittle to serve engineering purpose
- Tempering is necessary to increase ductility and toughness of martensite. Some hardness and strength is lost.
- Tempering consist on reheating martensitic steels (solution supersaturated of carbon) to temperatures between 150-500º C to force some carbide precipitation.

1st stage 80-160º C

\[ \alpha' \rightarrow \alpha''(\text{low C martensite}) + \varepsilon_{\text{carbide}} (\text{Fe}_{2.3}\text{C}) \]

2nd stage 230-280º C

\[ \gamma_{\text{retained}} \rightarrow \text{bainite} \]

3rd stage 160-400º C

\[ \alpha'' + \varepsilon_{\text{carbide}} \rightarrow \alpha + \text{Fe}_3\text{C}(\text{tempered martensite}) \]

3rd stage (cont) 400-700ºC

Growth and spherodization of cementite and other carbides
Martempering

A process to prevent the formation of quench cracks in the steel.

Cooling is carried out, as fast as possible, to a temperature over the $M_S$ of the steel.

The steel is maintained at $T>M_S$ until the inner core and outer surface of the steel component is at the same temperature.

The steel is then cooled below the $M_F$ to obtain 100% martensite. There is a need to increase the ductility of this steel by tempering.
**Austempering**

A process to prevent the formation of quench cracks in the steel.

Cooling is carried out, as fast as possible, to a temperature over the $M_S$ of the steel.

The steel is maintained at $T>M_S$ until the austenite transforms to 100% bainite.

There is no need of tempering post treatment.
Hardenability

Hardenability is the ability of the Fe-C alloy to transform to martensite during cooling. It depends on alloy composition and quenching media.

Hardenability should not be confused with “hardness”. A qualitative measure of the rate at which hardness decreases with distance from the surface because of decreased martensite content.

High hardenability means the ability of the alloy to produce a high martensite content throughout the volume of specimen.

Hardenability is measured by the Jominy end-quench test performed in a standard procedure (cylindrical specimen, austenitization conditions, quenching conditions - jet of water at specific flow rate and temperature).
Hardenability

Ability to be hardened by the formation of martensite as a result of heat treatment

Jominy End-Quench Test

Rockwell Hardness

Distance from quenched end

Different Cooling rate !!
Hardness versus Cooling Rate

Continuous Cooling Transformation

Hardenability Curve

Cooling rate

Distance from quench end
High carbon content, better hardenability
Use the hardenability data in the generation of hardness profile.

Larger specimen, lower cooling rate

Closer to the center, lower the cooling rate

Example