TIME-TEMPERATURE-TRANSFORMATION DIAGRAM

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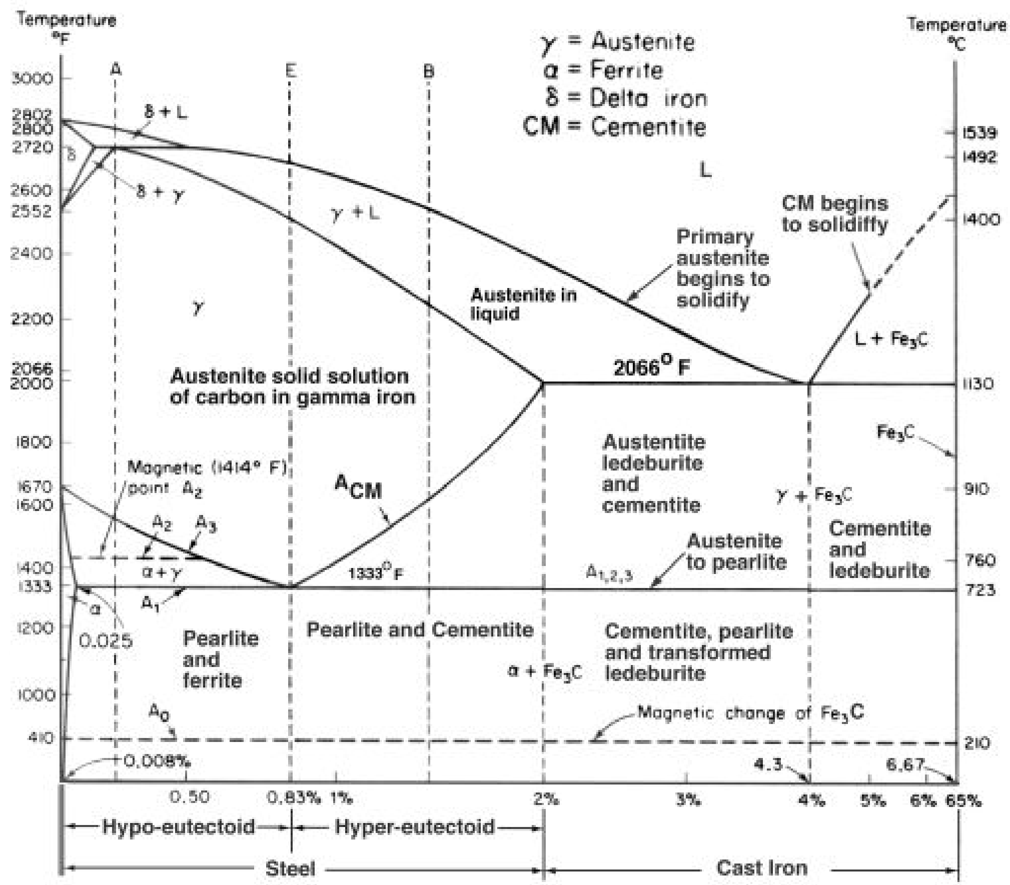
Phase Transformations in Steels

- Iron has having different crystal structures at different temperatures.
- It changes from FCC to BCC at 910^{o} C.
- This transformation results in austenite transforming to pearlite at eutectoid temperature.
- This transformation of austenite is time dependant.

Fe-C Equilibrium Diagram



Fe-C Equilibrium Diagram

- Though the Fe-C equilibrium diagram is very useful, it does not provide information about the transformation of austenite to any structure other than equilibrium structures, nor does it provide any details about the influence of cooling rates on the formation of different structures.
- In other words, Fe-C diagram does not explain the decomposition of austenite under non-equilibrium conditions or conditions involving faster rates of cooling than equilibrium cooling.
- Several structures (e.g. martensite) not appearing on the equilibrium diagram may be found in the microstructures in steels.

TTT Diagram

- On the other hand, TTT diagram is a more practical diagram.
- It shows what structures can be expected after various rates of cooling.
- It graphically describes the cooling rate required for the transformation of austenite to pearlite, bainite or martensite.
- TTT diagram also gives the temperature at which such transformations take place.

Phase diagram and TTT diagram

Which information are obtained from phase diagram or TTT diagram?

- Phase diagram :
  - Describes equilibrium microstructural development that is obtained at extremely slow cooling or heating conditions.
  - Provides no information on time taken to form phase

- TTT diagram
  - For a given alloy composition, the percentage completion of a given phase transformation on temperature-time axes is described.

Transformation Diagrams

- There are two main types of transformation diagrams that are helpful in selecting the optimum steel and processing route to achieve a given set of properties. These are

  1. Time-temperature transformation (TTT) diagrams

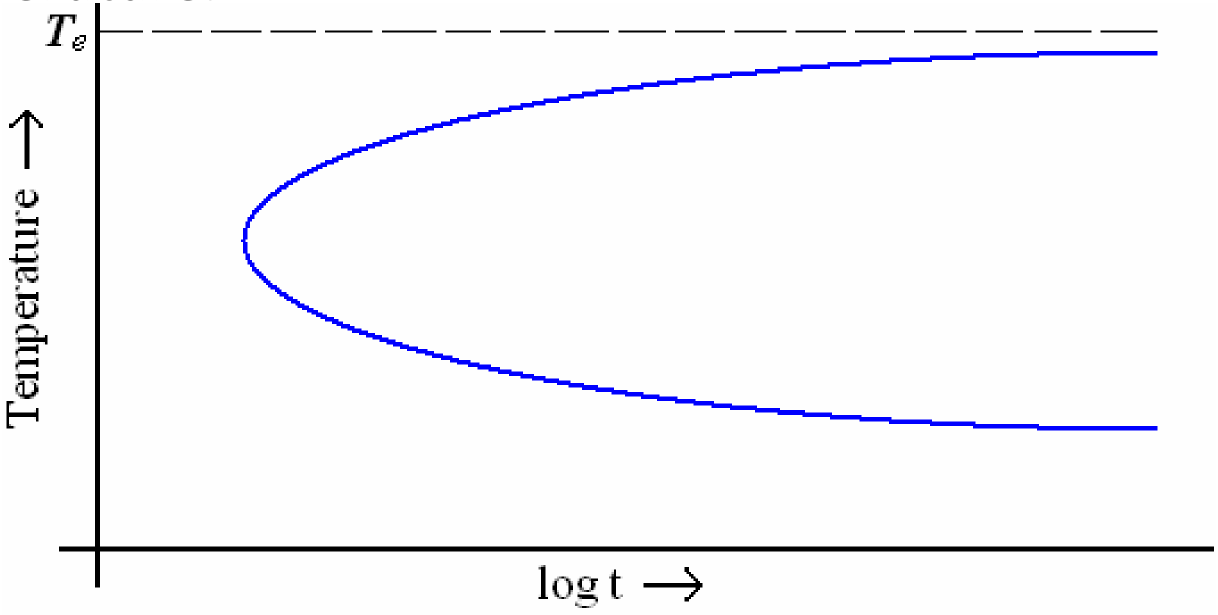
  2. Continuous cooling transformation (CCT) diagrams

How Transformation Occurs?

- Transformation of austenite to pearlite occurs by nucleation and growth mechanism.
- This transformation requires diffusion.

Time for Transformation

- *Time required for transformation as a function of temperature follows a reverse trend than the rate of transformation. Time required for transformation fist decreases, reaches a minimum and then starts increasing with decrease in temperature.*



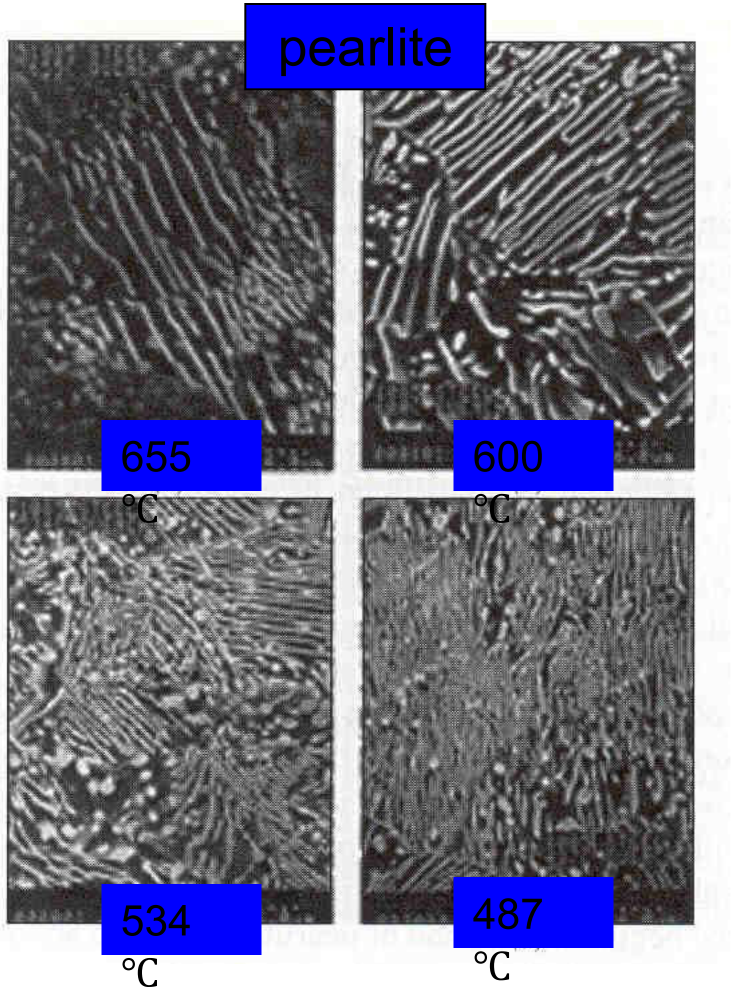
TRANSFORMATIONS OF AUSTENITE TO PEARLITE

Transformations of austenite :

$\gamma \rightarrow \alpha + Fe_3C$

1) At slightly lower T below 727 ℃ : $\Delta T <<$
   - Coarse pearlite
     : nucleation rate is very low.
     : diffusion rate is very high.
2) As the T (trans. temp.) decreases to 500 ℃
   - Fine pearlite
     : nucleation rate increases.
     : diffusion rate decreases.

Strength : σ (MPa) = 139 + 46.4 S^{-1}
S : inter-lamellar spacing



But at lower temperatures ….

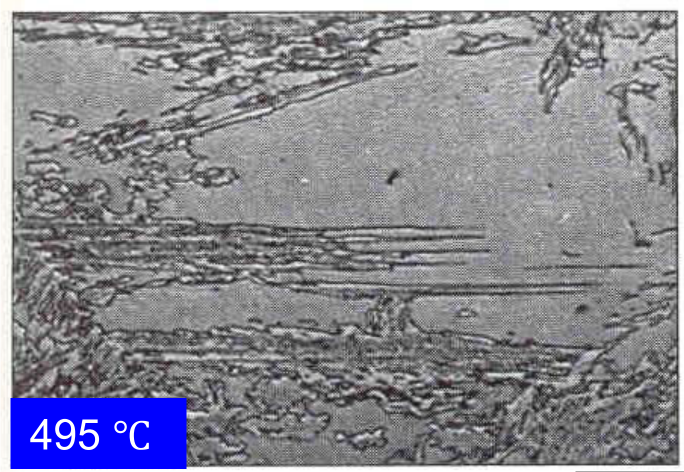
- At lower temperatures, the austenite transforms to bainite.
- Bainite is also a mixture of ferrite and cementite but not in the form of alternate layers.

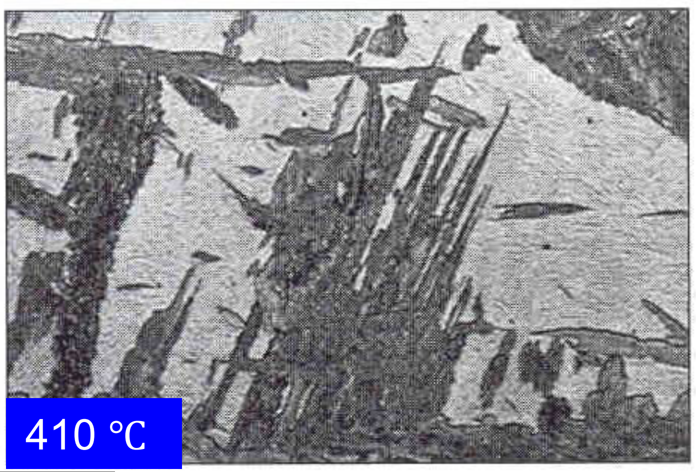
Transformations of austenite to Bainite

3) At further lower temperatures, 250 °C < T_t < 500 °C, below the nose in TTT diagram.

- Driving force for the transformation ($\gamma \rightarrow \alpha + Fe_3C$) is very high.
- Diffusion rate is very low.
- Nucleation rate is very high.

$\gamma \rightarrow \alpha + Fe_3C$ (But not in the form of alternate layers)
: Bainite ; cementite in the form of needle type.

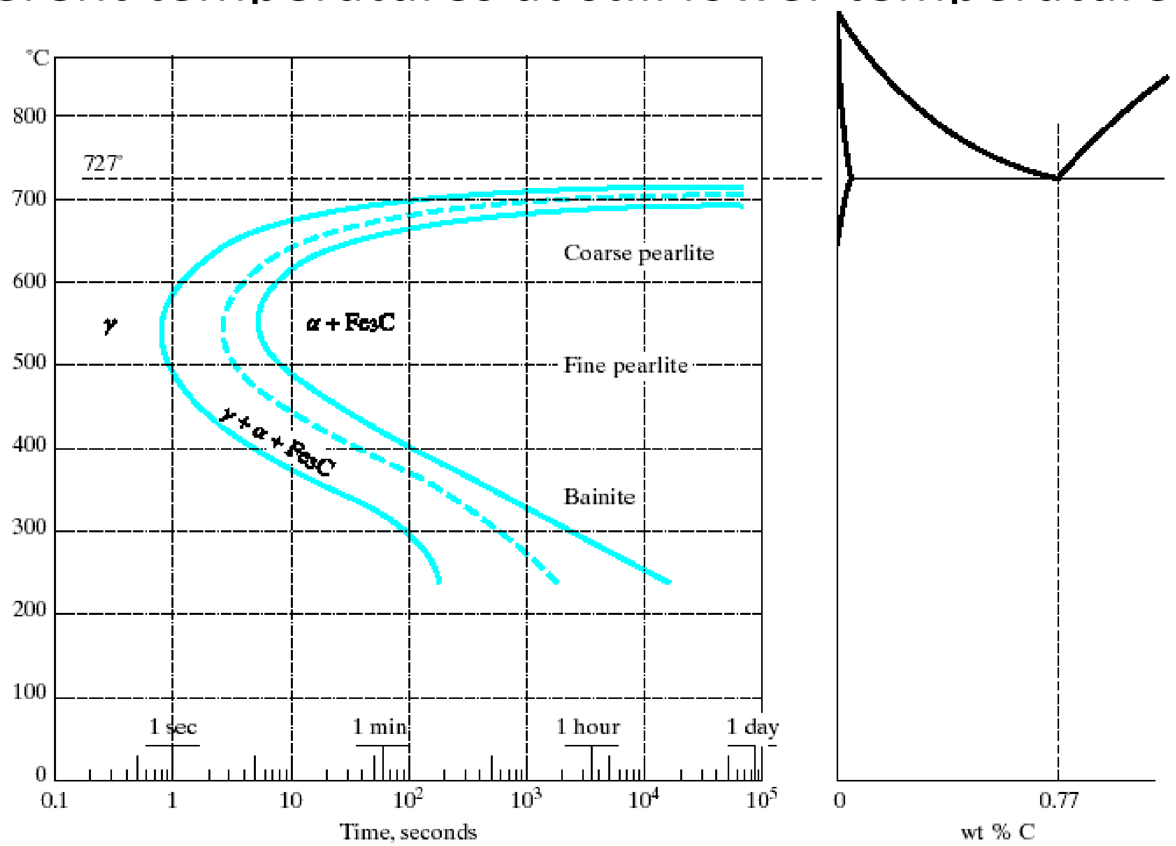




bainite

TTT diagram for eutectoid steel

- Plot the time for start and completion of transformation at different temperatures at still lower temperatures



On further decreasing the transformation temperature

- Below a certain temperature, the austenite changes or transforms to martensite.
- Martensite is a super saturated solid solution of carbon in α iron.
- It is a diffusionless transformation.
- It is also known as shear transformation as the interface between austenite and martensite moves as a shear wave at the speed of sound.

Transformations of austenite to Martensite

4. When the austenite is quenched to temp. below M_s

$\gamma \rightarrow \alpha'$ (martensite)

: Driving force for trans. of austenite → extremely high.

Diffusion rate is extremely slow.

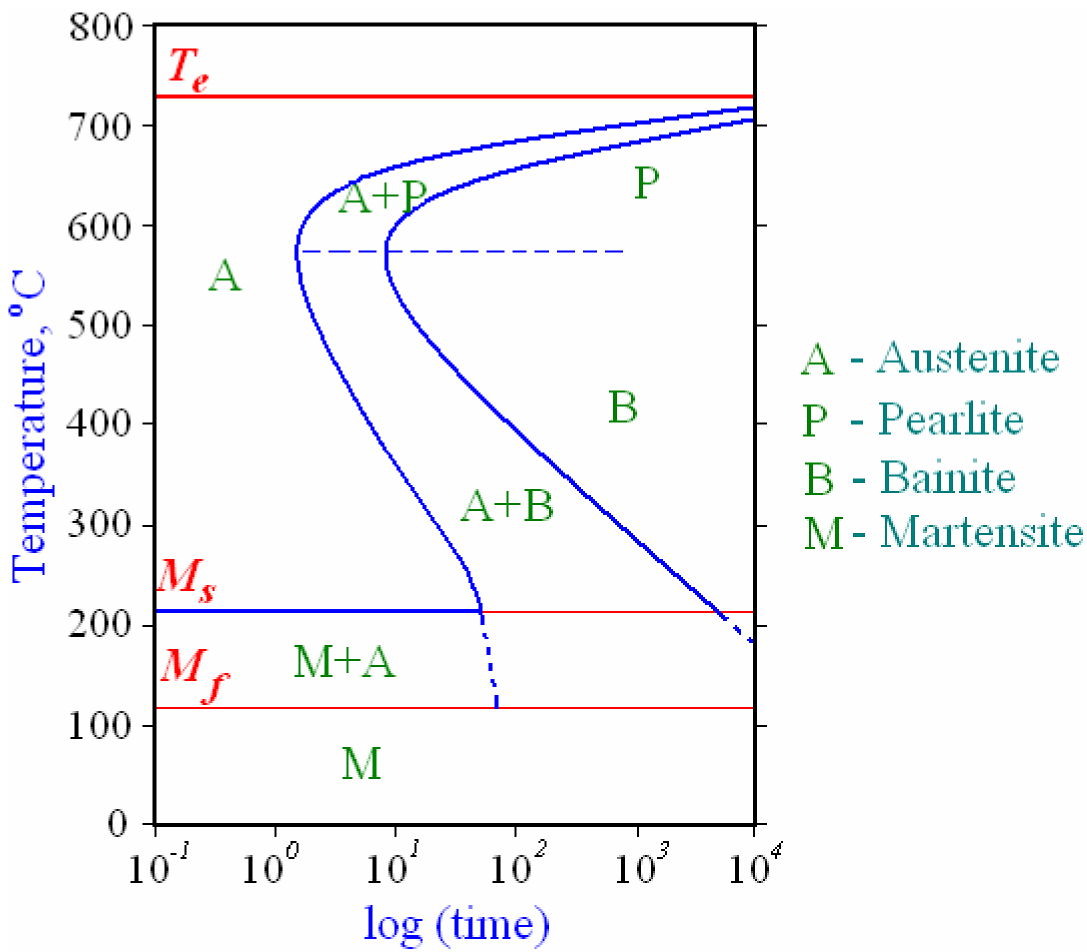
: Instead of the diffusional migration of carbon atoms to produce separate α and Fe_3C phases, the matensite transformation involves the sudden reorientation of C and Fe atoms from the austenite (FCC) to a body centered tetragonal (bct) solid solution.

$\gamma \rightarrow \alpha'$ (martensite), a super saturated solid solution of carbon in α iron formed by shear transformation (diffusionless transformation)

→ very hard and brittle phase

martensite

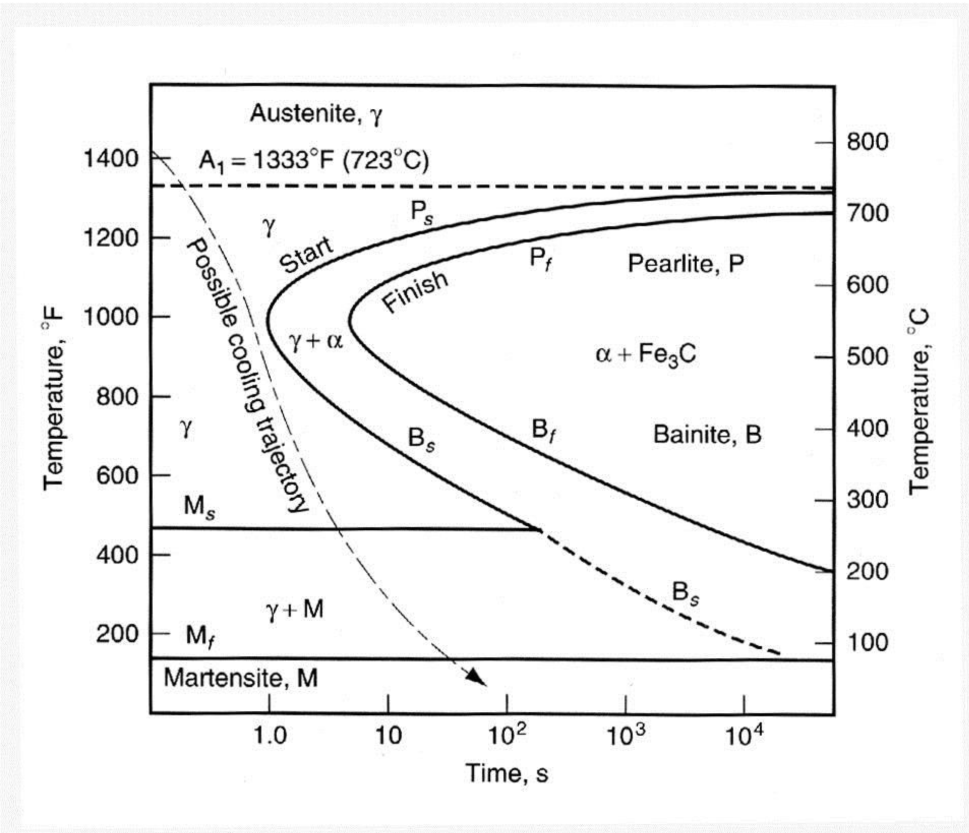
Complete TTT (isothermal transformation) diagram for eutectoid steel.



Time Temperature Transformation (TTT) Diagram

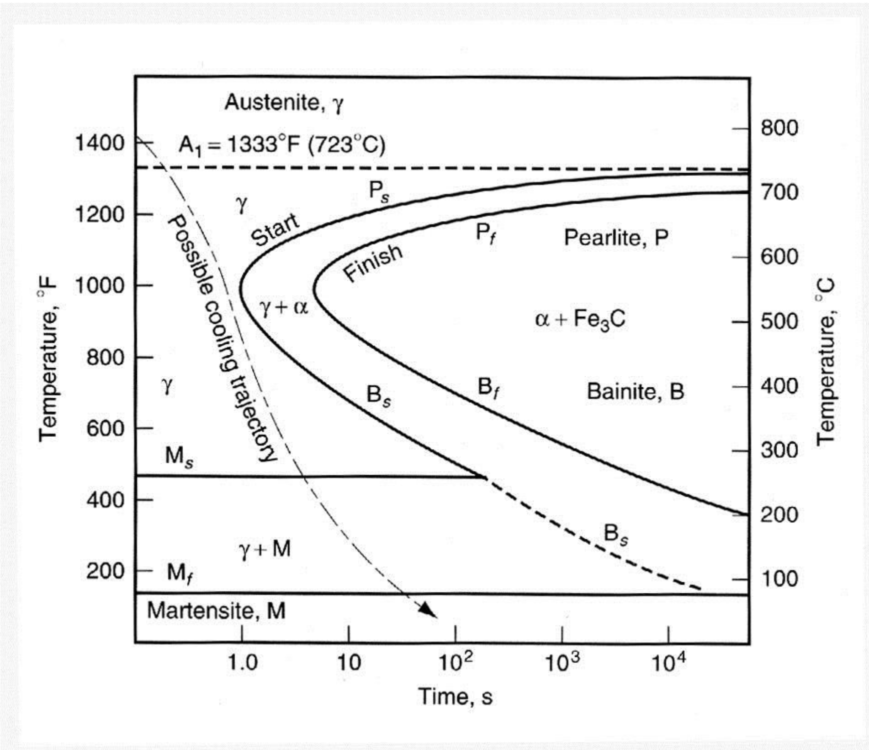
- Below A_1, austenite is unstable, i.e., it can transform into pearlite, bainite or martensite.
- The phases finally formed during cooling depend upon time and temperature.
- TTT diagram shows the time required for transformation to various phases at constant temperature, and, therefore, gives a useful initial guide to likely transformations.
- In addition to the variations in the rate of transformation with temperature, there are variations in the structure of the transformation products also.

The Time – Temperature – Transformation Curve (TTT)



- At slow cooling rates the trajectory can pass through the Pearlite and Bainite regions
- Pearlite is formed by slow cooling
  - Trajectory passes through Ps above the nose of the TTT curve
- Bainite
  - Produced by rapid cooling to a temperature above Ms
  - Nose of cooling curve avoided.

The Time – Temperature – Transformation Curve (TTT)



- If cooling is rapid enough austenite is transformed into Martensite.
  - FCC → BCT
  - diffusion separation of carbon and iron is not possible
- Transformation begins at M_s and ends at M_f.
  - If cooling is stopped at a temperature between M_s and M_f , it will transform into martensite and bainite .

Full TTT Diagram

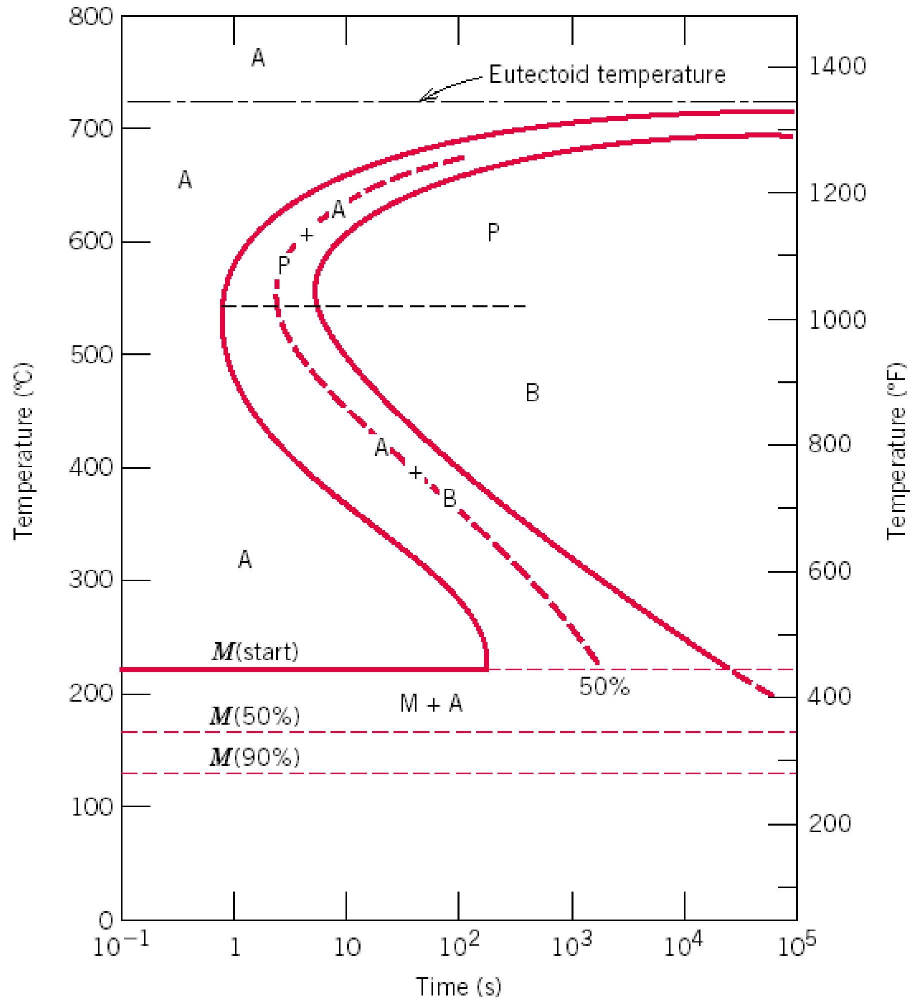
The complete TTT diagram for an iron-carbon alloy of eutectoid composition.

A: austenite

B: bainite

M: martensite

P: pearlite



TTT Diagram

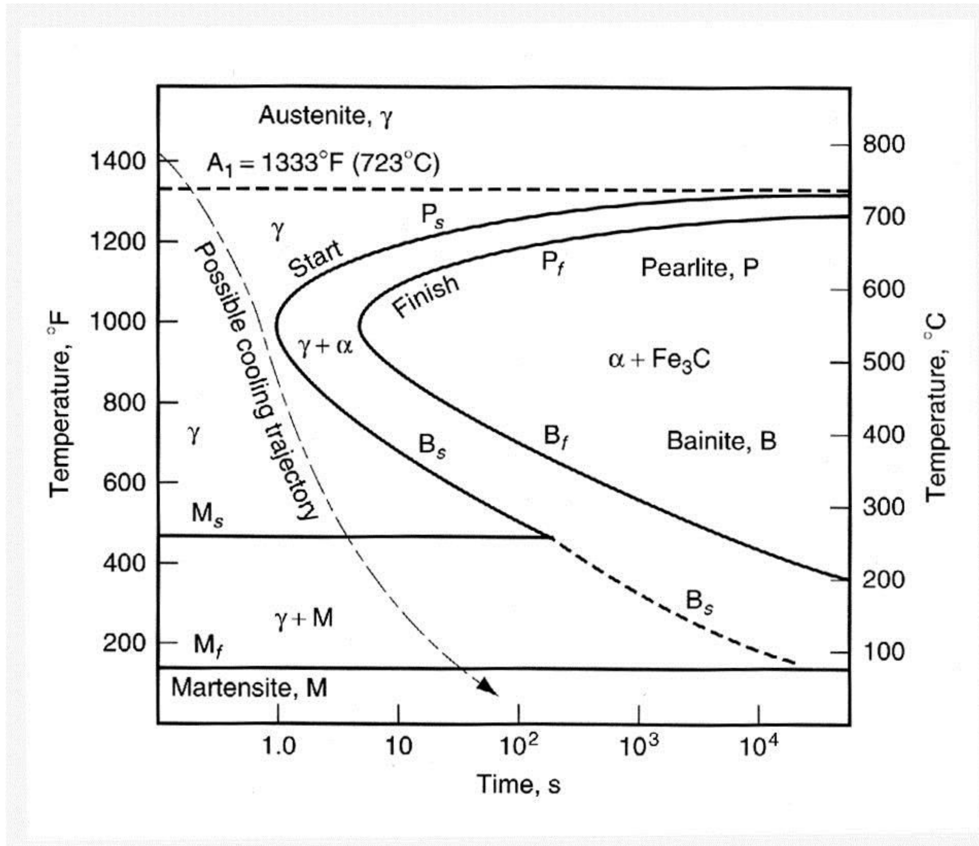
- Transformations at temperatures between approximately 705°C and 550°C result in the characteristic lamellar microstructure of pearlite.
- At a temperature just below A_1 line, nucleation of cementite from austenite will be very slow, but diffusion and growth of nuclei will proceed at maximum speed, so that there will be few large lamellae and the pearlite will be coarse.
- However, as the transformation temperature is lowered, i.e., it is just above the nose of the C-curve, the pearlite becomes fine.

Bainite

- At temperatures between 550°C and 240°C (the approximate, Ms temperature line), transformation becomes more sluggish as the temperature falls, for, although austenite becomes increasingly unstable, the slower rate of diffusion of carbon atoms in austenite at lower temperatures outstrips the increased urge of the austenite to transform. In this temperature range the transformation product is bainite.
- Bainite consists (like pearlite) of a ferrite matrix in which particles of cementite are embedded. The individual particles are much finer than in pearlite. The appearance of bainite may vary between
  - feathery mass of fine cementite and ferrite for bainite formed around 480°C and
  - dark acicular (needle shaped) crystals for bainite formed in the region of around 310°C).

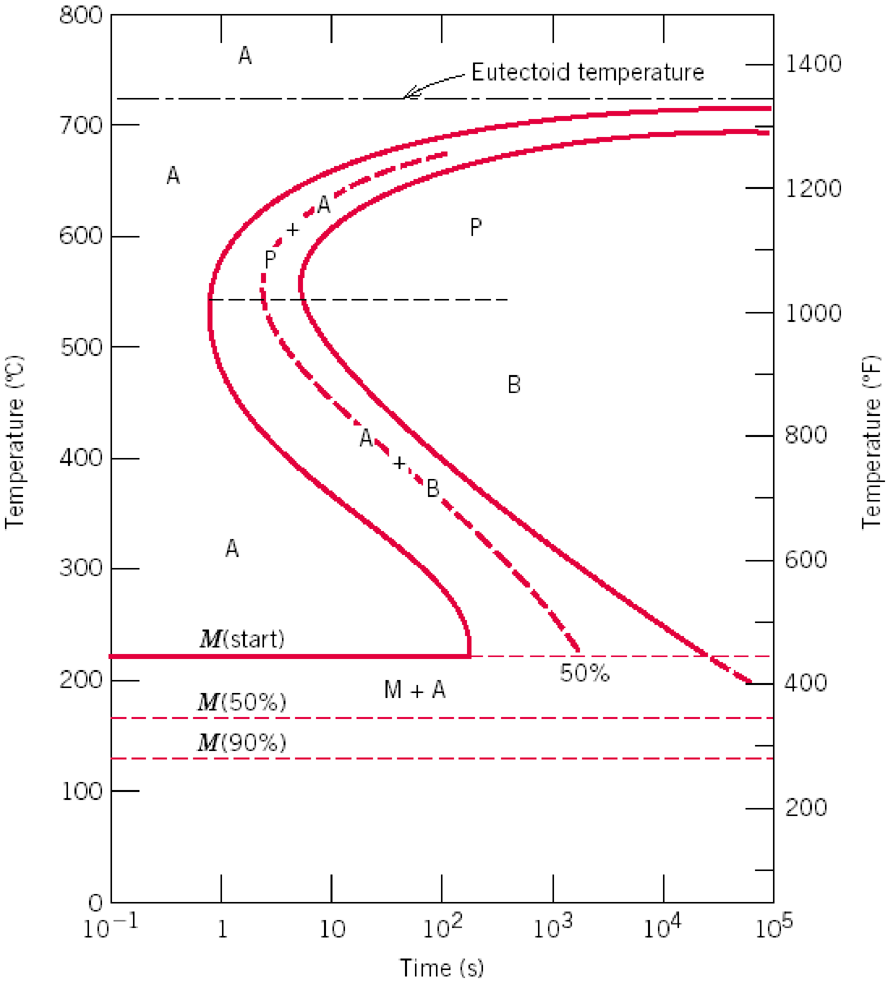
Martensite

- At the foot of the TTT diagram, there are two lines M_s (240°C) and M_f (50°C).
- Ms represents the temperature at which the formation of martensite will start and M_f the temperature at which the formation of martensite will finish during cooling of austenite through this range.



Martensite

- Martensite is formed by the diffusionless transformation of austenite on rapid cooling to a temperature below 240°C (approximately) designated as Ms temperature.
- The martensitic transformation differs from the other transformations in that it is not time dependent and occurs almost instantaneously, the proportion of austenite transformed to martensite depends only on the temperature to which it is cooled.
- For example the approximate temperatures at which 50% and 90% of the total austenite will, on quenching, transform to martensite are 166°C and 116°C respectively.

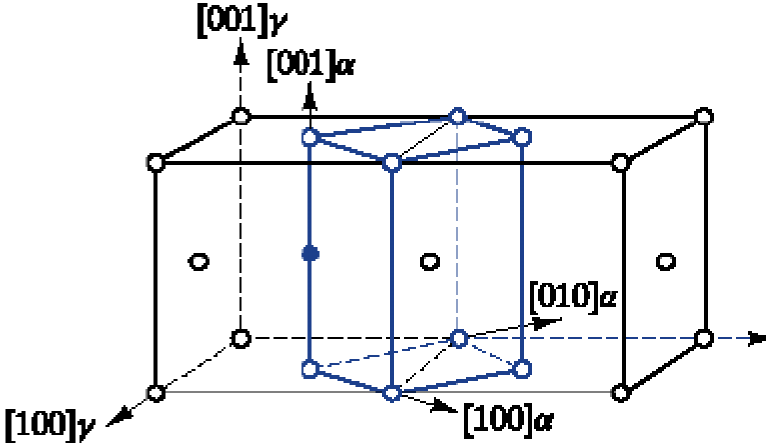


Martensite

(i) Martensite is a metastable phase of steel, formed by transformation of austenite below Ms temperature.
(ii) Martensite is an interstitial supersaturated solid solution of carbon in iron having a body-centered tetragonal lattice.
(iii) Martensite is normally a product of quenching.
(iv) Martensite is very hard, strong and brittle.

Martensite

- Diffusionless transformation of FCC to BCT (more volume)
- Very hard & very brittle.



Factors Affecting TTT Diagram

- 1. Grain size
- 2. Carbon content
- 3. Alloying elements

Effect of Grain Size

- Fine grain steels tend to promote formation of ferrite and pearlite from austenite.
- Hence decrease in grain size shifts the TTT diagram towards left.
- Therefore, critical cooling rate increases with decrease in grain size.

Effect of Carbon Content

- There is a significant influence of composition on the TTT diagrams. For the transformation diagrams we see the effect through a shift in the transformation curves. For example:
  - An increase in carbon content shifts the TTT curves to the right (this corresponds to an increase in hardenability as it increases the ease of forming martensite - i.e. the cooling rate required to attain martensite is less severe).
  - An increase in carbon content decreases the M_s (martensite start) temperature.

Effect of Alloying Elements

- Different alloying elements have their different effects on TTT diagram.
- An increase in alloy content shifts the TTT curves to the right and
- Alloying elements also modify the shape of the TTT diagram and separate the ferrite + pearlite region from the bainite region making the attainment of a bainitic structure more controllable.

THANKS