# ME 216 – Engineering Materials II

**Chapter 12**

Heat Treatment (Part I)

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- **Heat treatment** is heating and cooling a metal in solid state to change its physical properties.

- According to the procedure used, metals can be hardened to resist cutting and abrasion, or can be softened to permit further machining. Therefore, with proper heat treatment:
  - *internal stresses can be removed*
  - *grain size can be reduced*
  - *toughness can be increased*
  - *a hard surface can be produced on a ductile interior*

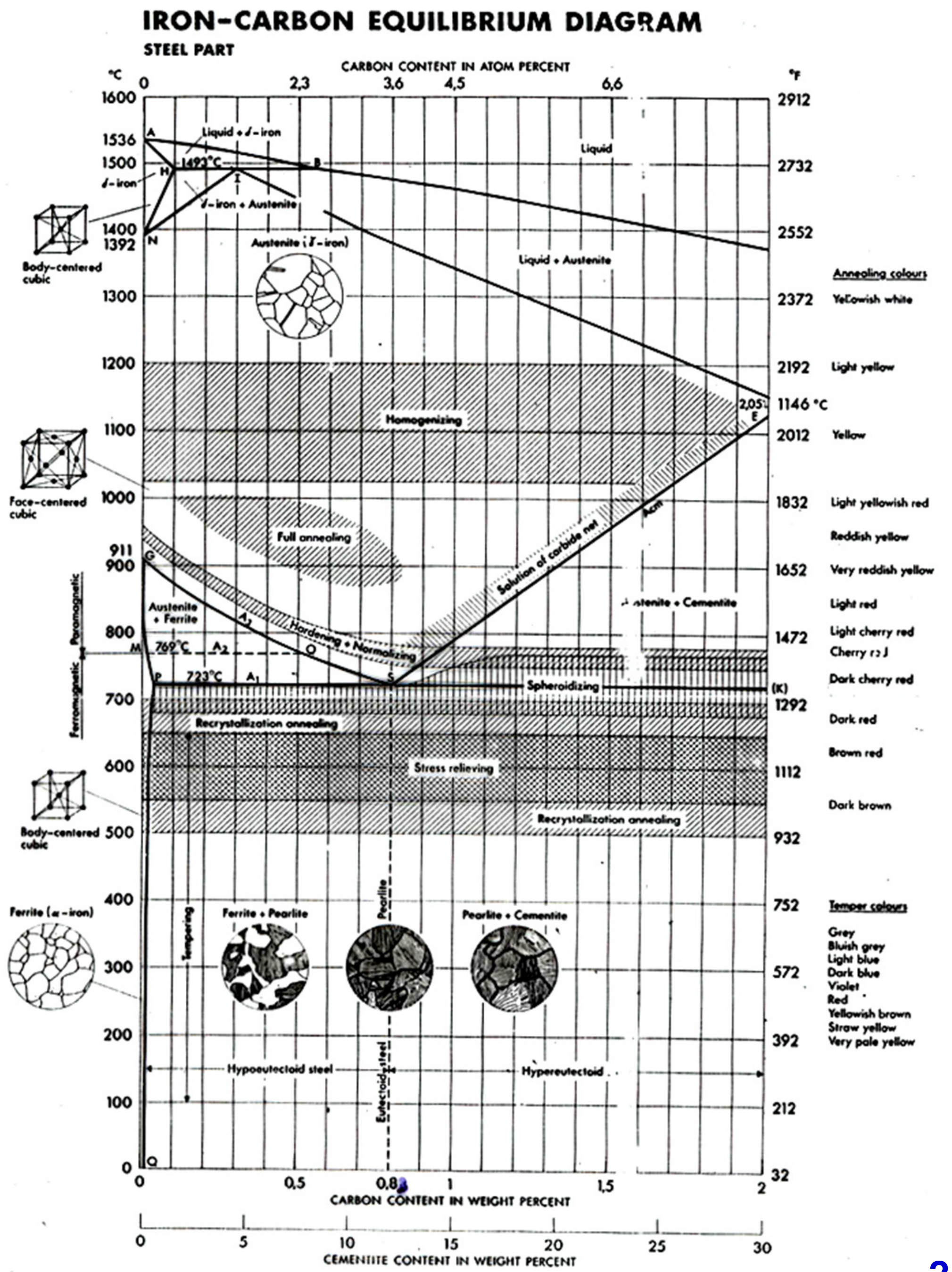
- Phases and microstructures in a metal can be modified, thus combination of properties most suitable for a given application can be chosen.

- The microstructures of **single-phase metals** can be adjusted by:
  - *plastic deformation*
  - *recrystallization*
  - *solid solution additions*
  - *crystal orientation*

- In addition, there are additional means of control of microstructures in **multi-phase metals**:
  - *The relative amounts of the phases may be varied.*
  - *The grain size may be varied.*
  - *The shape and distribution of phases can be modified.*

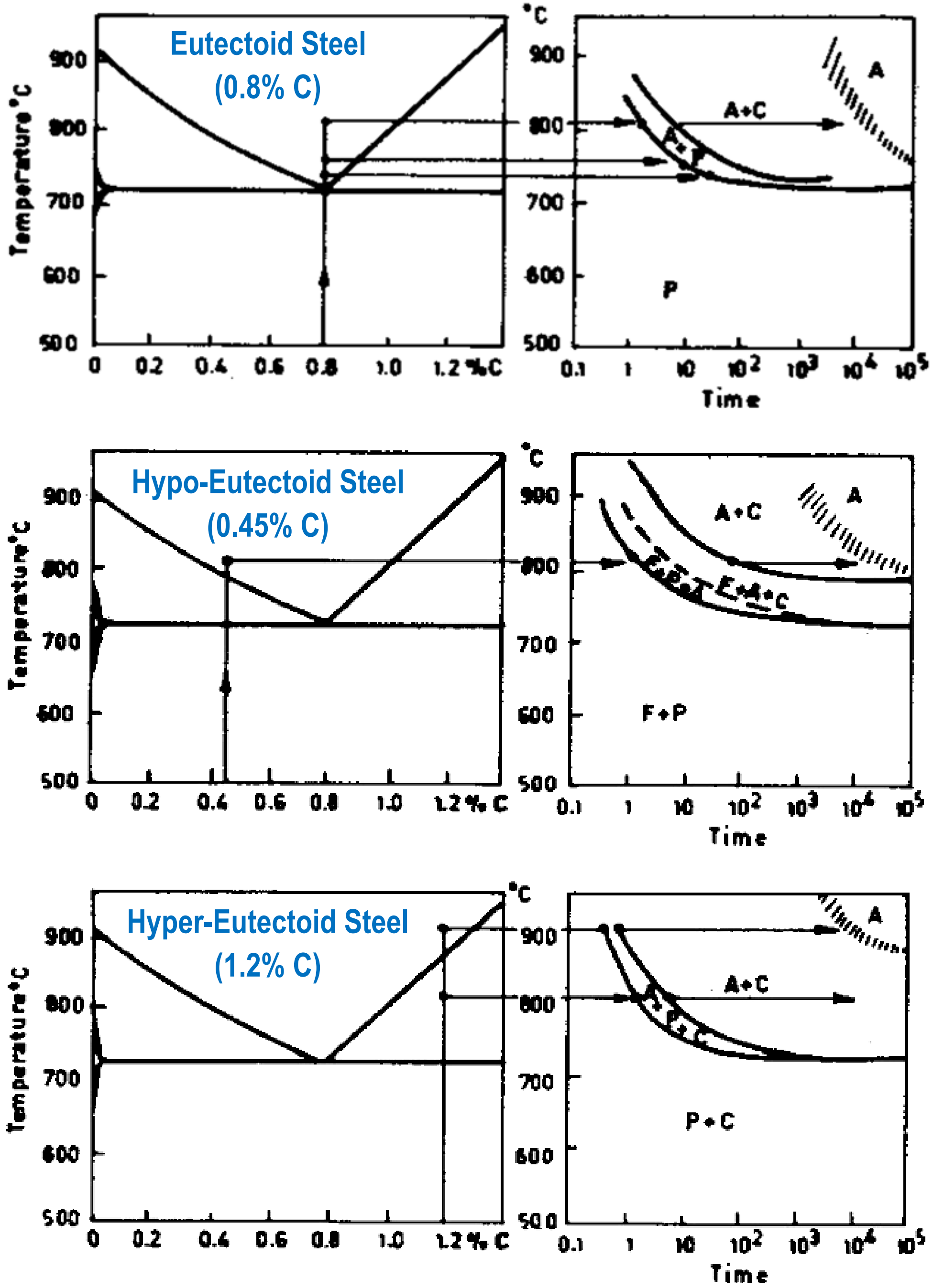
- Each of these three microstructural variations provides means of modifying the properties of metals.

- On heating pure iron from room temp. to its melting point, it undergoes **allotropic modifications**. On cooling molten iron to room temp, **transformations take place in the reverse order** (at approximately the same temperatures as on heating).
- **$\alpha$-iron** is stable below 911 °C, **$\gamma$-iron** is stable between 911 °C and 1392 °C, and **$\delta$-iron** is stable between 1392 °C and 1536 °C (melting point).
- Iron is ferromagnetic at room temp. Its magnetism vanishes completely at 769 °C.
- Carbon is the most important alloying element in steel. At room temp, the solubility of **C** in **$\alpha$-iron** is almost zero. Thus, it separates from crystal structure and forms a chemical compound with iron, which is known as cementite. Cementite and ferrite may show a lamellar structure, which is known as pearlite.
- When **Fe** is alloyed with **C**, the transformation will take place within a temp. range, which is dependent on **C** content as shown in **Fe-C** equilibrium diagram. Solubility of carbon in austenite is much greater than in ferrite (i.e. 2% **C** at 1193 °C).



# Time-Temperature-Transformation (TTT)

- **Fe-C** diagram can only describe the situation when equilibrium is established between **Fe** & **C**.
- However, in heat treatment operation, time of heating and cooling is also a significant factor.




## Heating

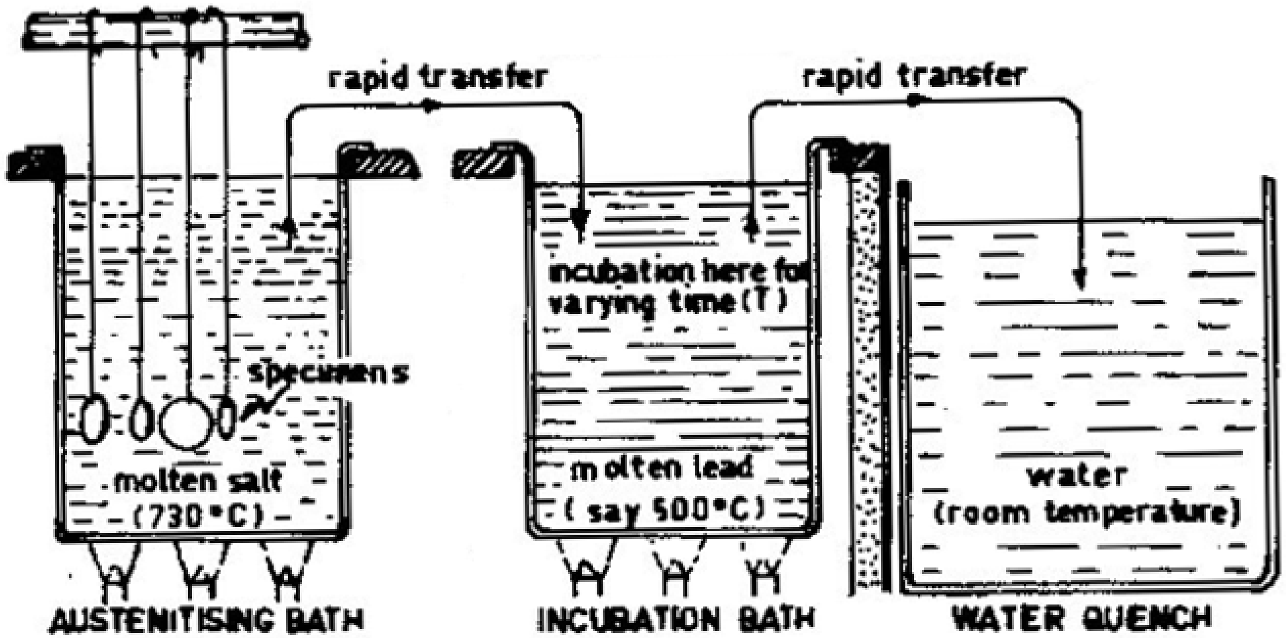
- On heating **eutectoid steel (0.8% C)**, phase diagram shows that the transformation to austenite occurs at **723 °C**. However, it tells us nothing about how long this transformation will take to start and to complete.
- **From heating curve**, it can be predicted that when temp. is **730 °C**, transformation starts in **30 s**. If steel is heated to **750 °C** transformation begins in **10 s**, and if heated to **810 °C** it begins in **1 s**.
- Transformation of pearlite to austenite & cementite is completed in about **6 s** at **810 °C**. If steel is to be fully austenitic, it must be held at this temp. for about **5 h**.
- Transformations of **hypo-eutectoid steel (0.45% C)** and **hyper-eutectoid steel (1.2% C)** are also shown.

## Cooling

- General appearance of a structure during cooling is dependent upon temp. and time of transformation.
- The transformation of steel at a certain temp. can be investigated by cooling from austenite to that temp, letting the transformation take place, and then quenching to room temp.

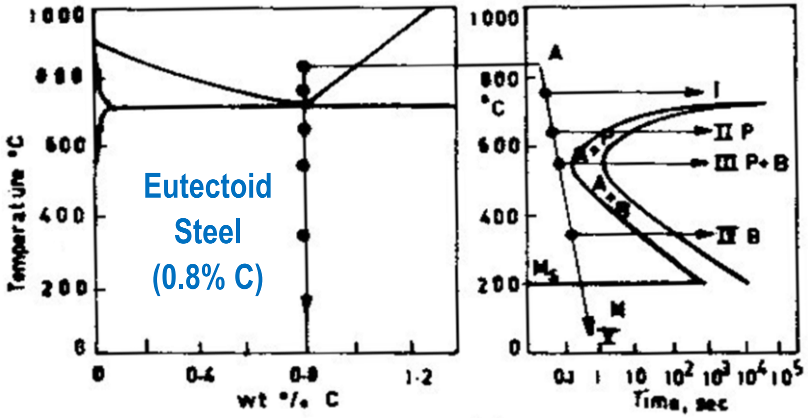
- This is best explained by construction of **Time-Temperature-Transformation (TTT) diagrams**:

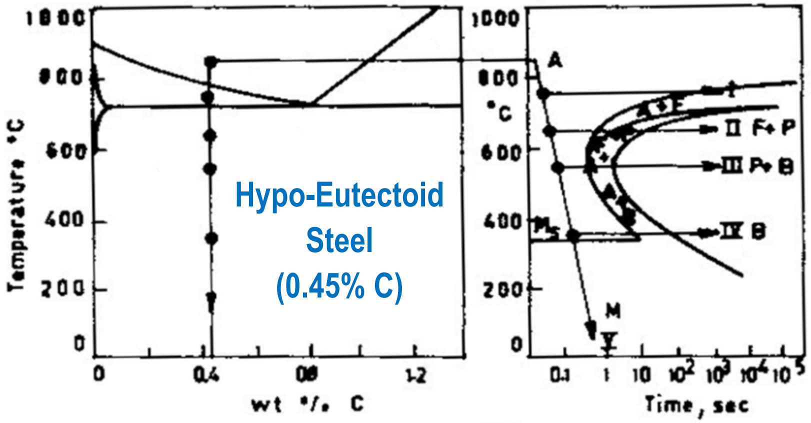
1. Prepare samples from the same bar. Cross-section must be small for quick reactions to changes in temp.
2. Place samples in a molten salt bath at the proper austenitizing temp. They should be held at this temp. long enough to become purely austenite.
3. Place samples in an incubation bath, held at a constant subcritical temp.
4. After varying duration, each sample is quenched in cold water or iced brine.
5. After cooling, each sample is checked for hardness and structure.

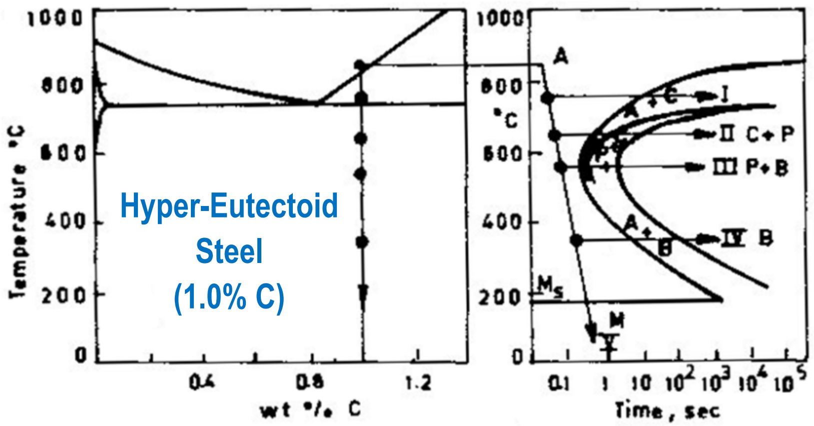


## Cooling

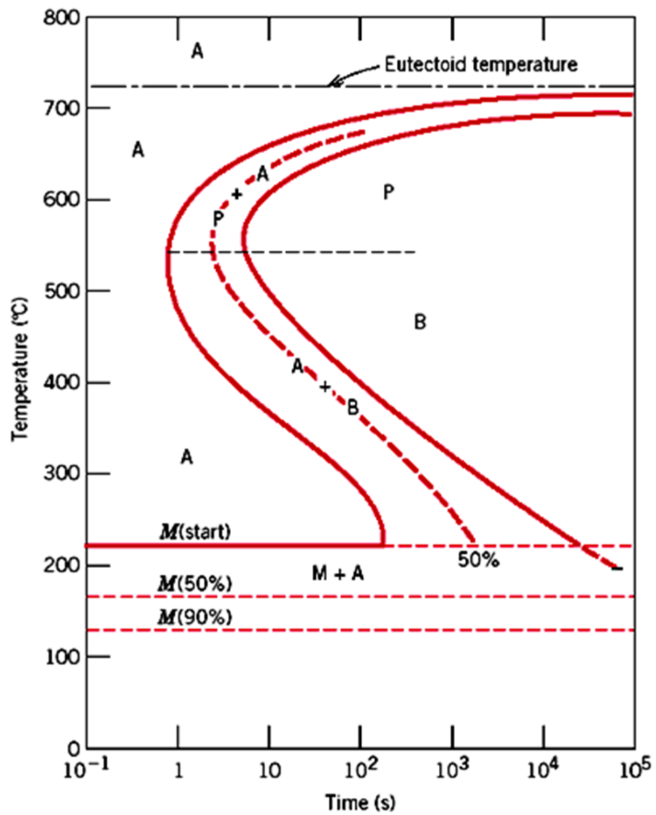
- As a result of such experiments, two points are plotted at subcritical temp: **the times for beginning and end of transformation**. It is also common practice to plot the time for 50% transformation.
- Construction of a reasonably accurate diagram requires heat treatment and metallographic study of more than one hundred individual samples.
- ***TTT diagrams for different steels are shown in figures.***



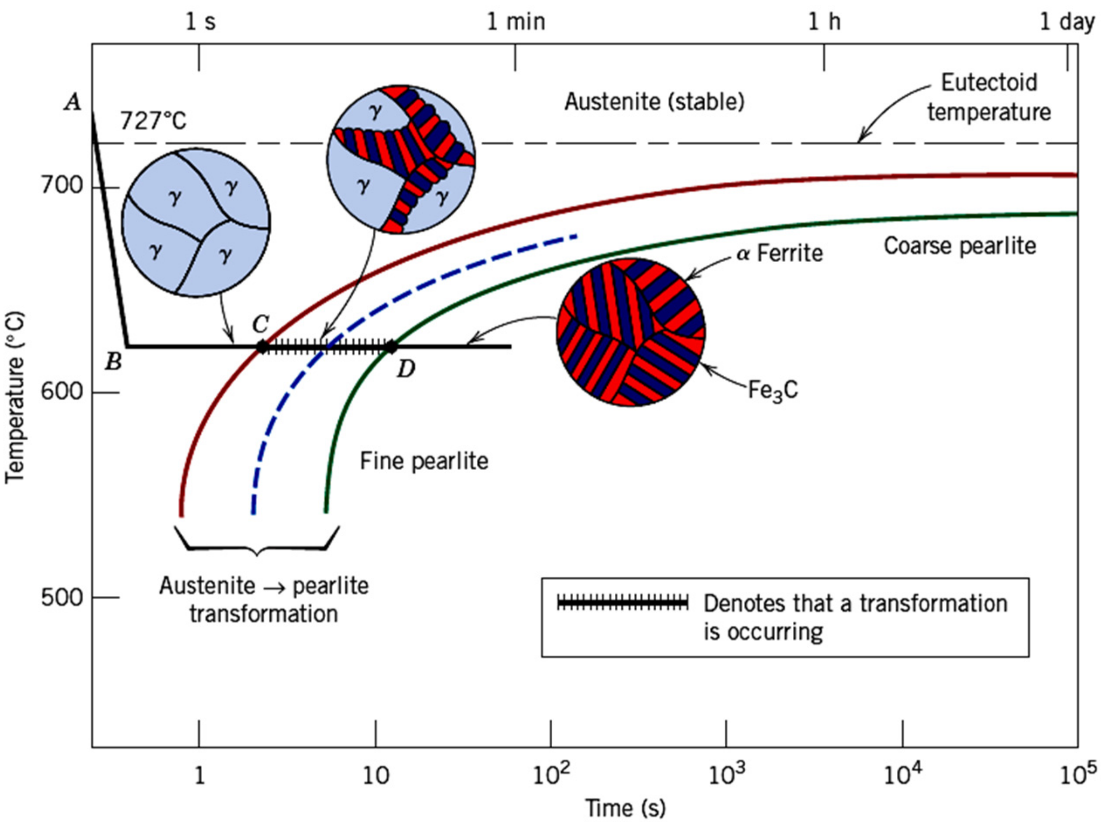
- Family of S-shaped curves at certain constant temp. are used to construct the TTT diagrams.
- They are used for isothermal (constant temp.) transformations (i.e. the material is cooled quickly to a given temp. before transformation occurs, and then kept at that temp.)
- **At low temp**, transformation occurs sooner (controlled by rate of nucleation) with slow grain growth (controlled by diffusion). This leads to fine-grained microstructure with thin-layered structure of pearlite **(fine pearlite)**.
- **At high temp**, high diffusion rates allow for larger grain growth and formation of thick-layered structure of pearlite **(coarse pearlite)**.
- At compositions other than eutectoid, a proeutectoid phase (ferrite or cementite) coexists with pearlite. Additional curves for such transformation must be included on TTT diagrams.




Complete TTT diagram for Fe-C alloy of **eutectoid composition**

# Formation of Pearlite

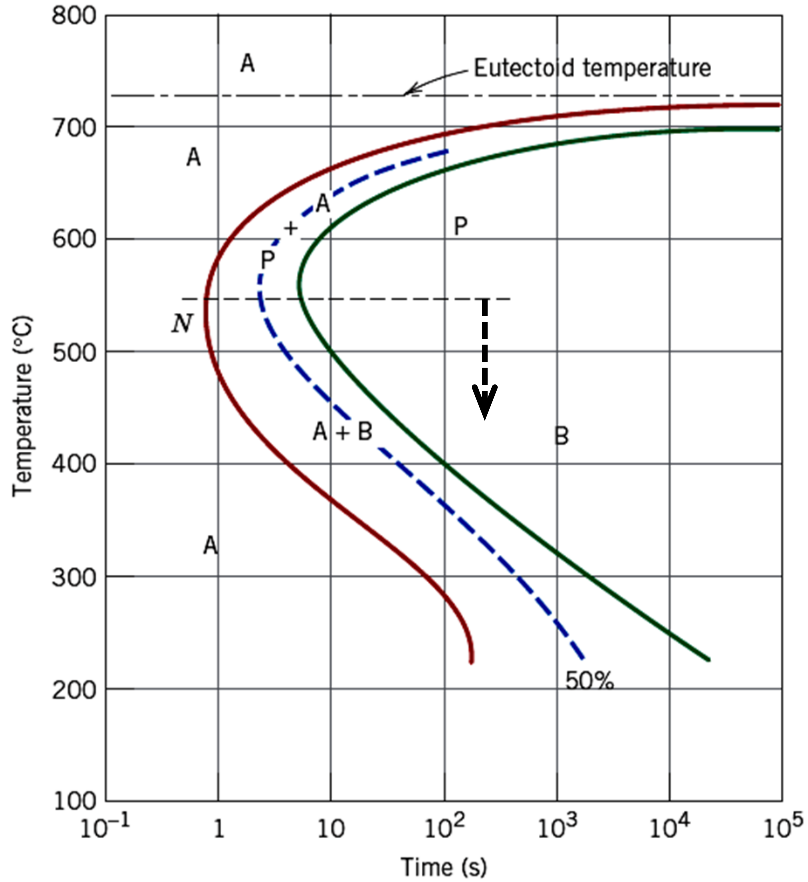
- **Pearlite** is the characteristic lamellar structure of alternate layers of **ferrite (α)** and **cementite ($Fe_3C$)**.
- Just below 723 °C (eutectoid temp, $T_E$), **coarse pearlite** is formed with soft structure (about 15 HRC).
- As transformation temp. decreases, **fine pearlite** is obtained, and the whole structure becomes harder.
- Pearlite formation is initiated at austenite (γ) grain boundaries or at some other disarray in γ grains. First, **$Fe_3C$** is initiated (causing carbon depletion in adjacent regions), then transformed to α platelets.

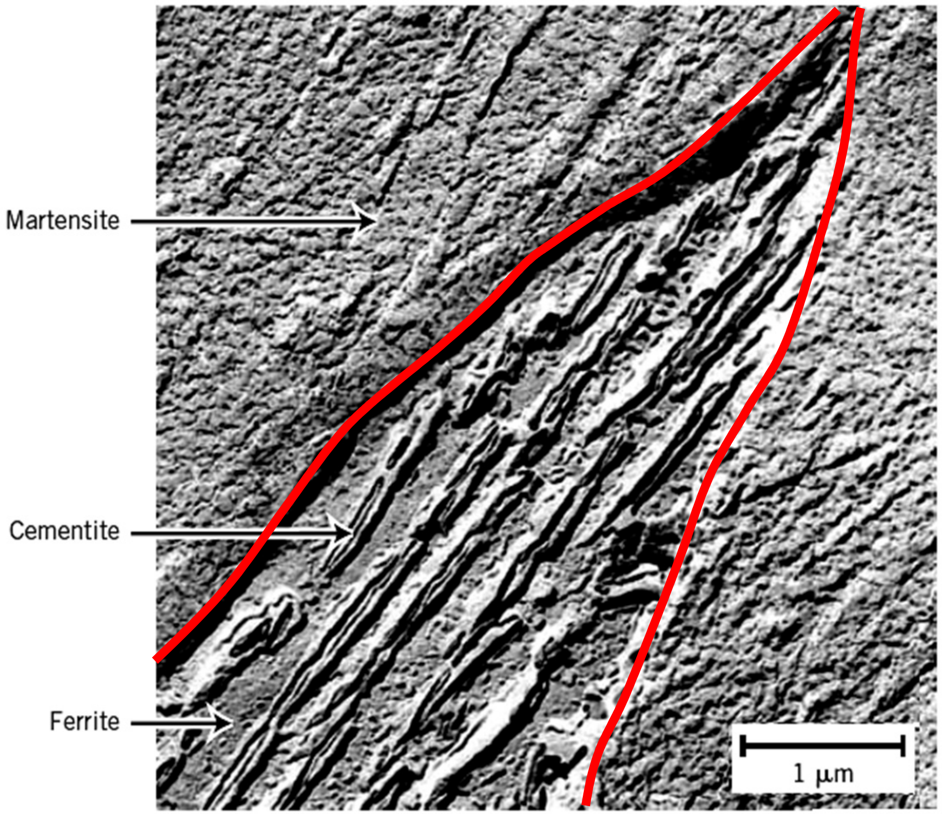



**Coarse Pearlite**
(softer, formed at just below $T_E$)


**Fine Pearlite**
(harder, formed at well below $T_E$)

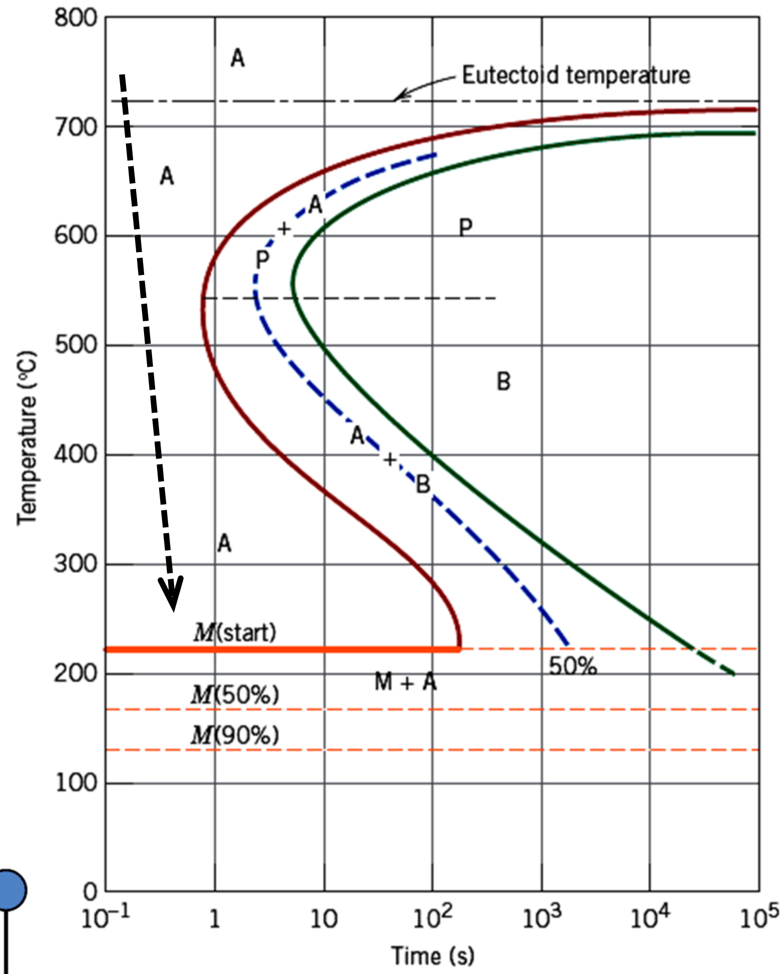
- Below 550 °C, **bainite** starts to separate along with pearlite.
- Its formation is initiated on nuclei of $\alpha$, growing as platelets from grain boundaries. The carbon content of surrounding $\gamma$ increases continuously, and forms platelets of **$Fe_3C$**.
- Bainite structure is not regularly lamellar as that of pearlite.



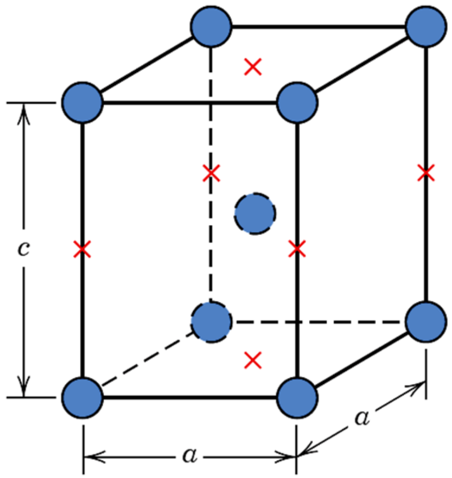




- Depending on temp. of formation, it is classified as:
  - **upper bainite** (from hardness of about **40 HRC**)
  - **lower bainite** (to hardness of about **60 HRC**)
- Such increase in hardness is resulting from decrease in size & spacing of carbide platelets since transformation temp. decreases.

- **Martensite** is formed if austenitized structure is rapidly cooled (quenched) to a relatively low temp (about room temp).
- As cooling continues, there is very little carbon migration while γ is transforming. Thus, carbon atoms remain in solid solution of **α-iron**. As the space available for carbon atoms is less in **α-iron** than **γ-iron**, carbon atoms will expand the lattice. The resulting state of stress increases the hardness of steel.
- Martensite is a super-saturated solution of carbon in **α-iron**.
- As seen from diagram, each temp. below **martensite start (Ms)** corresponds to a definite proportion of martensite.

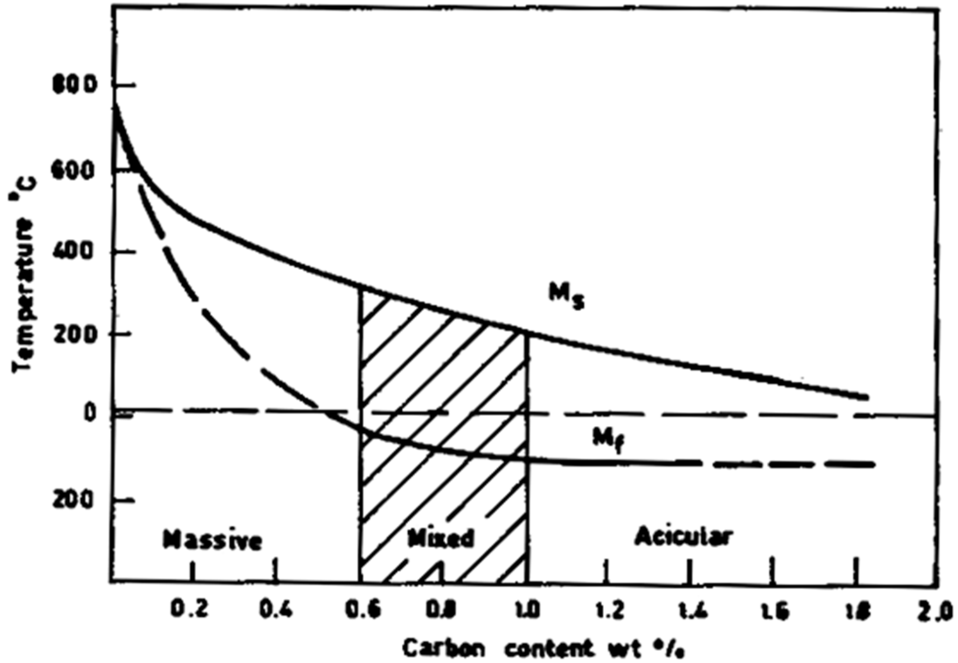



Martensite phase (needle-shaped grains) with austenite (white regions that failed to transform during rapid quench)

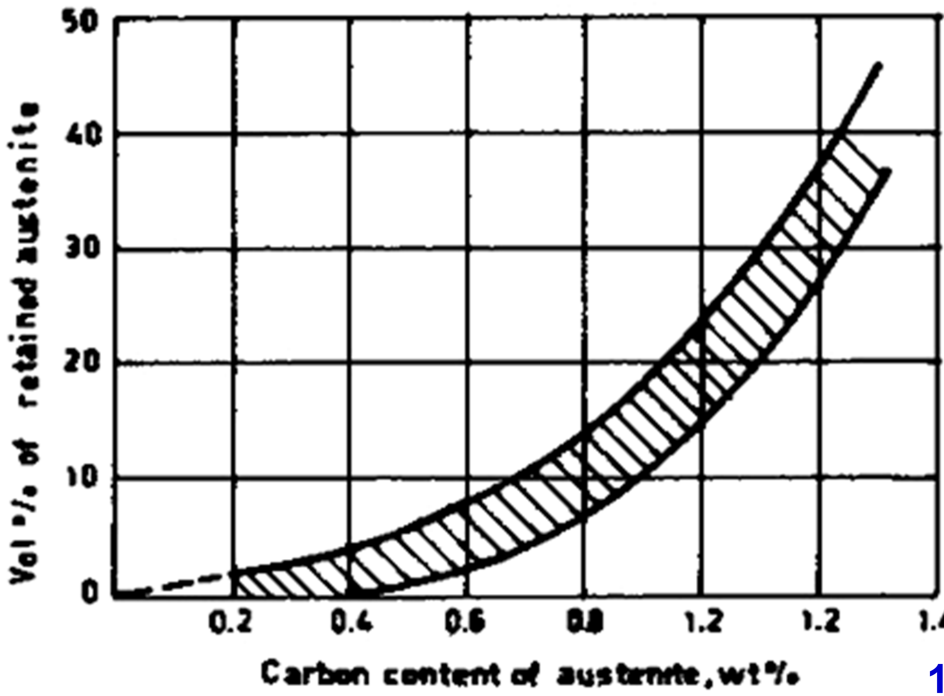

**Body-centered tetragonal unit cell (c > a)** for martensitic steel structure, showing **iron atoms (circles)** and sites occupied by **carbon atoms (Xs)**.

- Martensite structure in steels is classified as:
  - **massive martensite:** Steels having up to 0.6% C. Consists of packets of parallel platelets that can only be resolved in electron microscope.
  - **acicular martensite:** More familiar martensite, found only in steels having 1% C or more.




## Retained-Austenite

- Most of γ in steel will transform to martensite during quenching to room temp. The untransformed portion is **retained austenite**, **varying with carbon content**.
- If temp. is below room temp, the transformation to martensite continues. This way of increasing amount of martensite is called **sub-zero treatment**.
- In **martempering process**, cooling is interrupted just above **Ms**, so steel is allowed to cool to room temp. This stabilizes γ, causing martensite formation to start at a lower temp, thus resulting in a higher proportion of retained austenite at room temp.
- So, **martempered (air-hardened) steel** has larger amount of retained austenite than **oil-hardened one**.



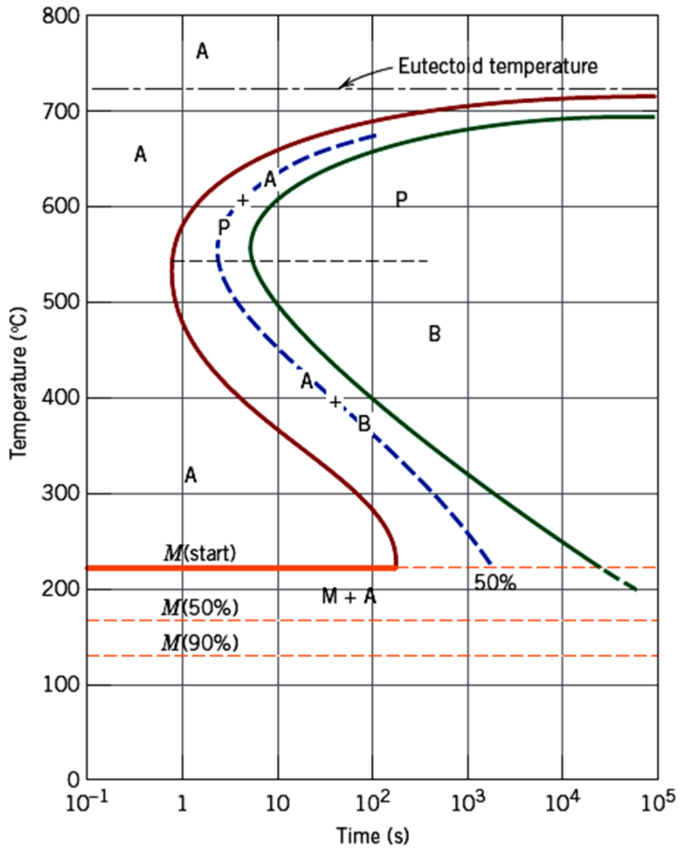
# Effect of Alloying Elements on TTT Curves

- Alloying elements delay formation of $\alpha$ and **$Fe_3C$** (i.e. **curves in TTT diagram are shifted to the right**).
- **Start temp. for transformation** of **bainite (Bs)** and **martensite (Ms)** are altered by following equations:

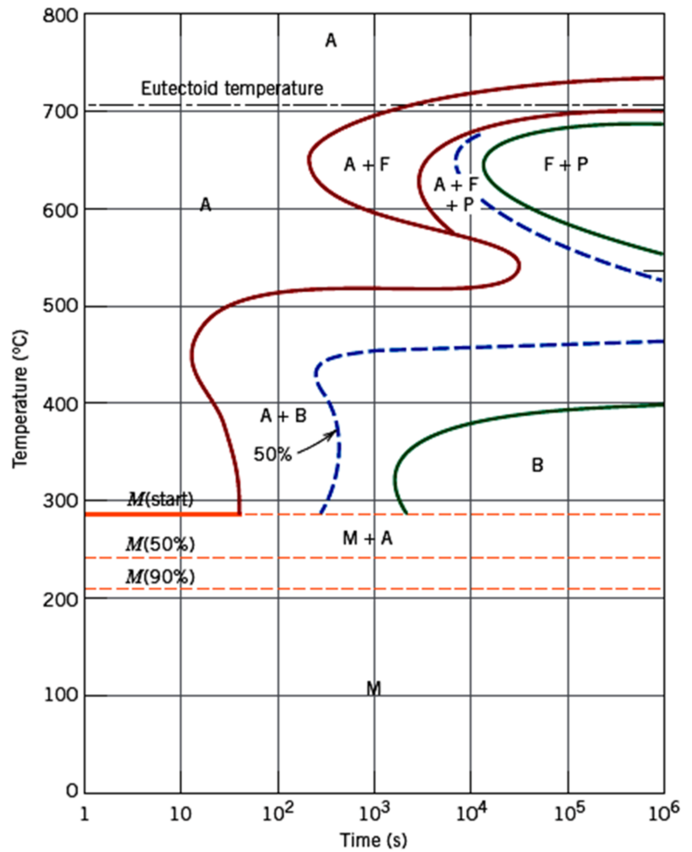
$$B_s(°C) = 830 - 270(\%C) - 90(\%Mn) - 37(\%Ni) - 70(\%Cr) - 83(\%Mo)$$

$$M_s(°C) = 539 - 423(\%C) - 30.4(\%Mn) - 17.7(\%Ni) - 12.1(\%Cr) - 7.5(\%Mo)$$

- **C, Ni, Mn, Si** move pearlite and bainite curves to right, but not separating them appreciably on the temp. scale.
- **Mo, Cr, V** move pearlite curve markedly toward right and also displace it upwards to higher temp. However, bainite curve is not moved much toward right, but depressed to lower temp.




TTT diagram for **unalloyed eutectoid steel** (0.8% C)




TTT diagram for **an alloy steel (type 4340**: Ni-Cr-Mo with 0.4% C)

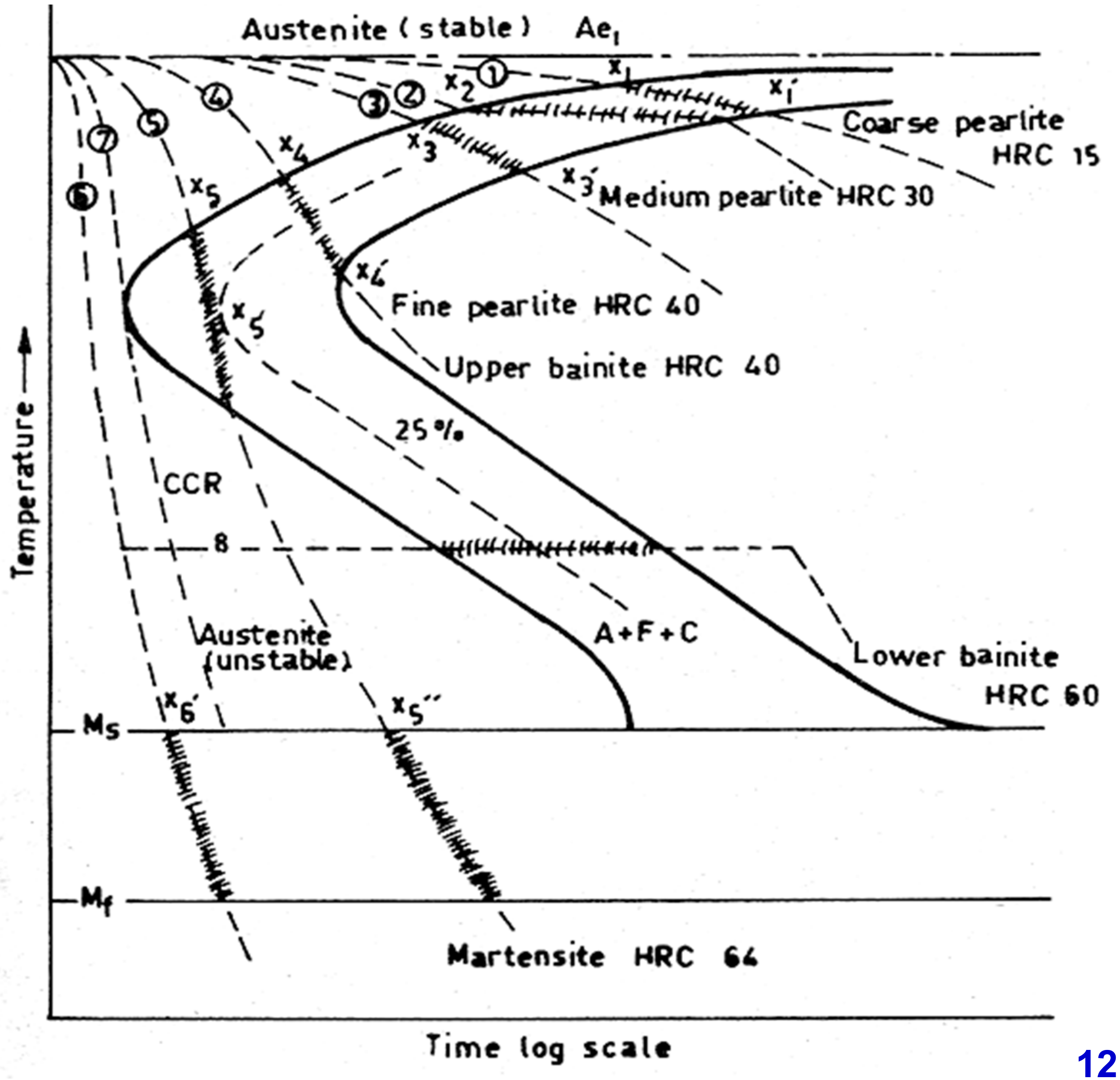
- TTT curves refer to transformation at a cst temp, but most heat treatment operations involve continuous cooling. From TTT diagrams, **Continuous Cooling Transformation (CCT) diagrams** are derived to show transformations under continuous cooling.

- Figure shows **CCT curves**, superimposed on TTT diagram of **an eutectoid steel**.

- **Curve 1** indicates a very slow cooling rate (typical of annealing), allowing transformation to coarse pearlite. Transformation starts at **X1** and completed at **X1'** after which material may be cooled without any change.

- **Curve 2** illustrates an isothermal annealing, which results in more uniform microstructure.

- **Curve 3** refers to cooling rate of normalizing: transformation starts at **X3** and completed at **X3'**. Time difference between these points is shorter than that in **Curve 1** (i.e. btw **X1** and **X1'**), and hence the structure will show more variation in the fineness of pearlite.

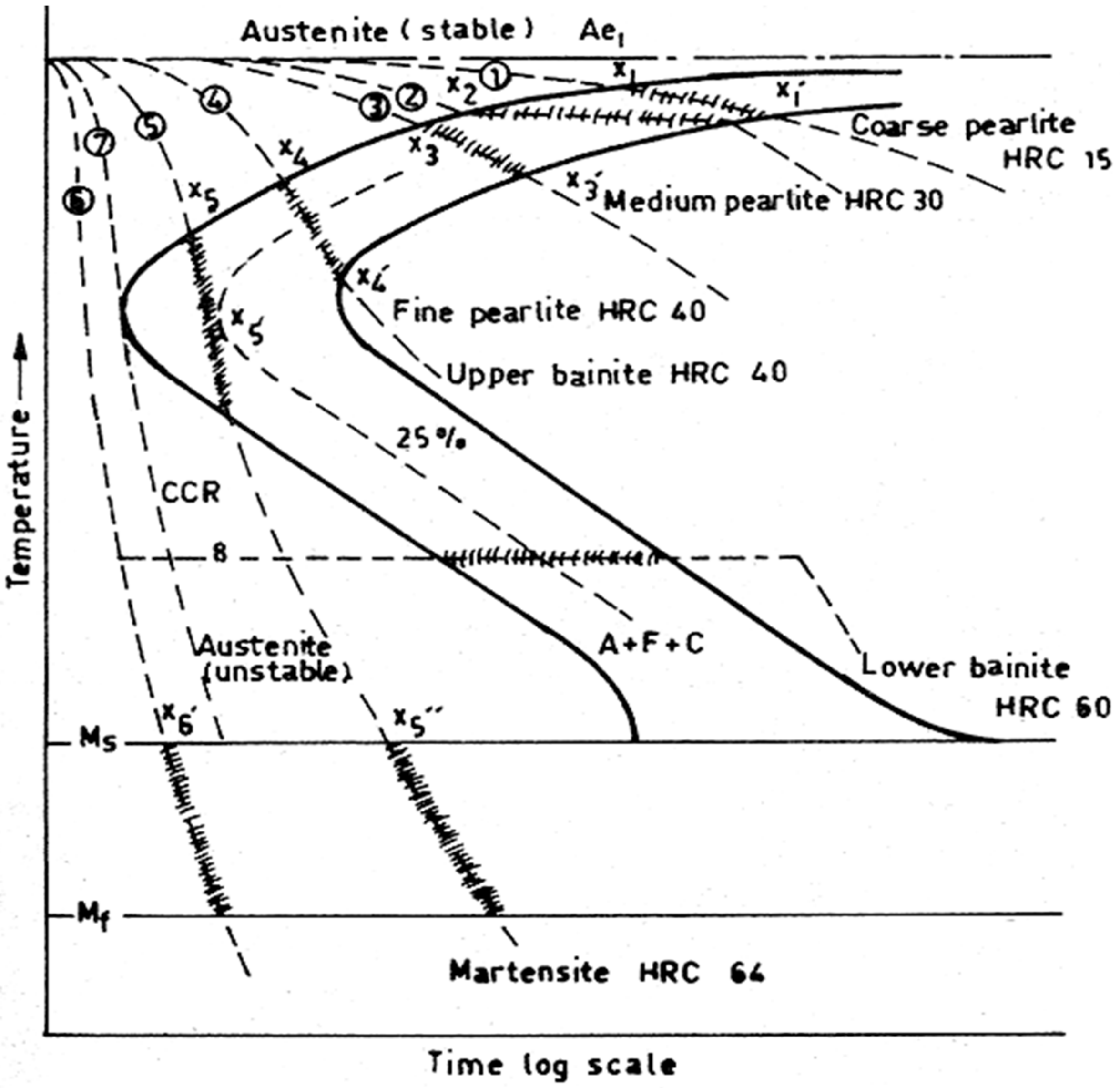


# Continuous Cooling Transformation (CCT)

- **Curve 4** is slow oil quenching, which results in fine pearlite.

- **Curve 5** is fast oil quenching: transformation to fine pearlite starts at **X5** and stops at **X5'**. Below this temp, no transformation occurs until **X5"** on the martensite start line (**Ms**). Thereby, remaining austenite transforms to martensite, and hence final microstructure is 25% fine pearlite and 75% martensite.

- **Curve 6** represents fast water quenching, which avoids nose of pearlite transformation. It remains austenitic until the martensite start line (**Ms**) is reached at **X6'**. Transformation to martensite occurs between lines of start (**Ms**) and finish (**Mf**). The final microstructure will be entirely martensite of high hardness.




- **Curve 7** is called Critical Cooling Rate (tangent to top pearlite nose region, which does not transform to pearlite). **Any cooling rate slower than critical rate** will enter pearlite region, so complete martensitic transformation will not occur. **Any cooling rate faster than critical rate** will form only martensite.

# An Example on using TTT diagrams

- On the given isothermal transformation diagram for **Fe-C alloy with 0.45% C**, sketch time-temp. paths to produce the following microstructures:

**a) 42% proeutectoid ferrite** & **58% coarse pearlite**
- First, produce ferrite
- Then, produce pearlite *(closer to $T_E$)*

**b) 50% fine pearlite** & **50% bainite**
- First, produce pearlite *(on the line of **P-B**)*
- Then, produce bainite *(middle of **B** region)*

**c) 50% martensite** & **50% austenite**
- Cool until middle of **M** region *(btw **Ms** & **Mf**)*

**d) 100% martensite**
- Quenching *(rapid cooling)* until room temp.