Heat Treatment Principles and Practices

Dr.K. Santhy
Associate Professor
Department of Materials and Metallurgical Engineering
Institute of Technology and Engineering
Indus University, Ahmedabad

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Introduction

- 80% alloys in industrial use are Fe-C alloy
- Purest form of Fe is 99.999% which contain 60 ppm impurities
  - 50ppm – metallic impurities

    10ppm – non-metallic impurities (like C, O, S, P)

Allotropy of Fe

Metals which exhibits more than one crystal structure depending on the temperature & or Pressure – Allotropy

Example :

Ti & Zr — HCP → BCC at 882 & 815^{o}C respectively

Sn — cubic(grey)→ Tetragonal(white) at 13.2^{o}C

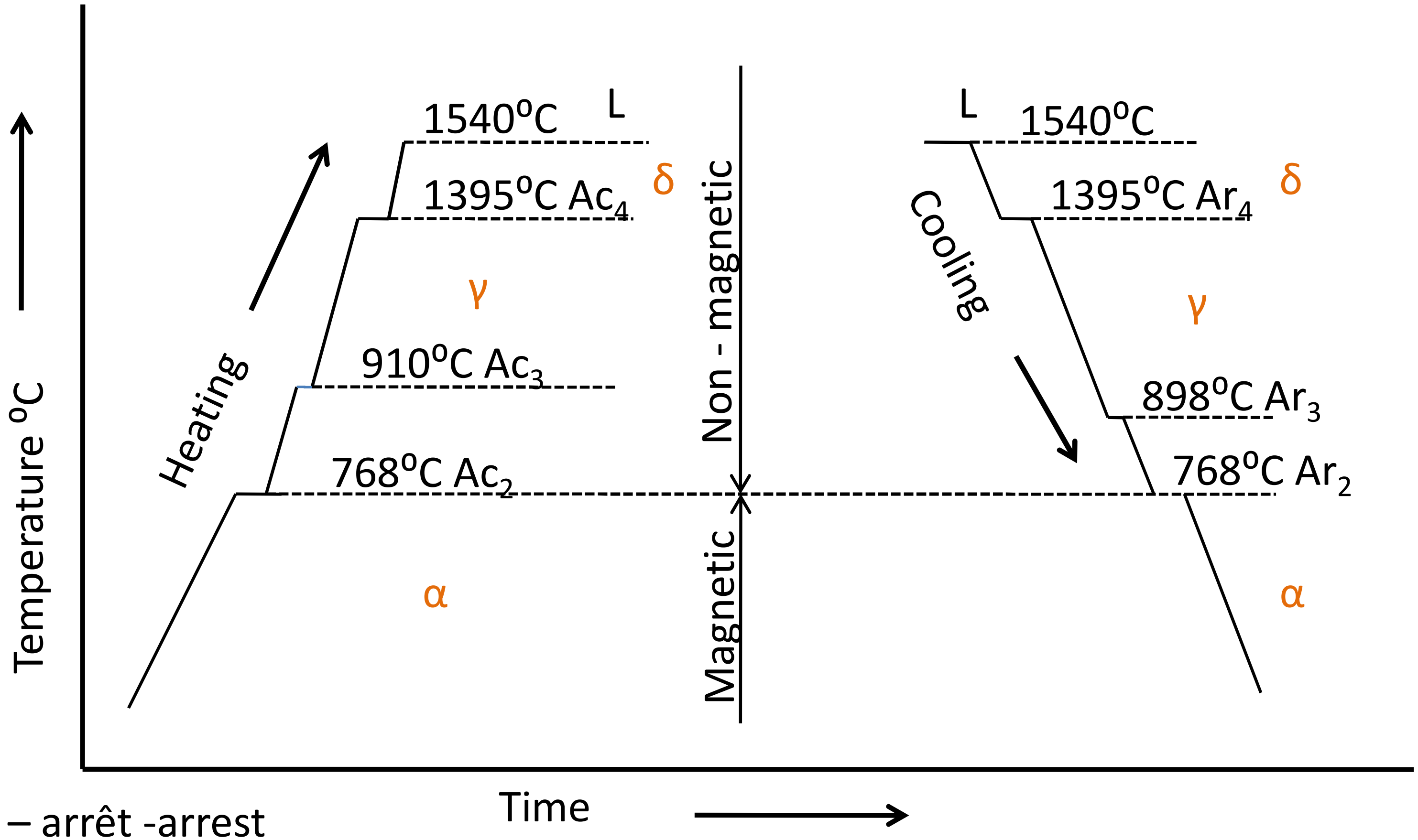
Plutonium — 6 allotropy (RT to T_m--640^{o}C)

Name	Crystal structure	Temp. range	No. of atoms in unit cell	Atomic packing density
α-Fe	BCC	< 910 ^{o}C	2	0.68
γ-Fe	FCC	910 – 1394 ^{o}C	4	0.74
δ-Fe	BCC	1394 – 1539 ^{o}C	2	0.68

Allotropy transition can be abrupt or sluggish

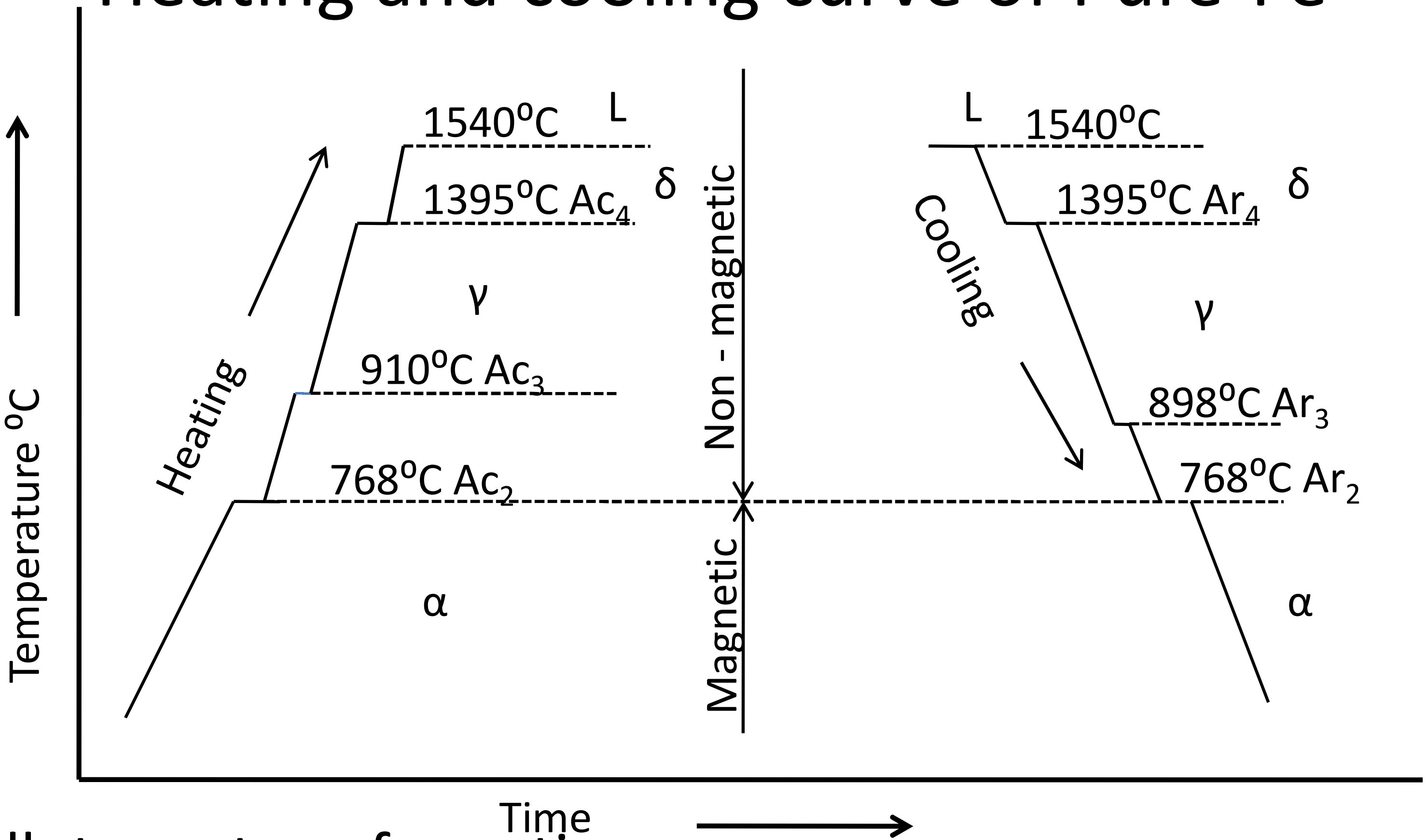
Volume change take place during transition

Heating and cooling curve of Pure-Fe



A – arrêt -arrest
r – refrodissement –cooling
c – chauffage - heating
French word in cooling

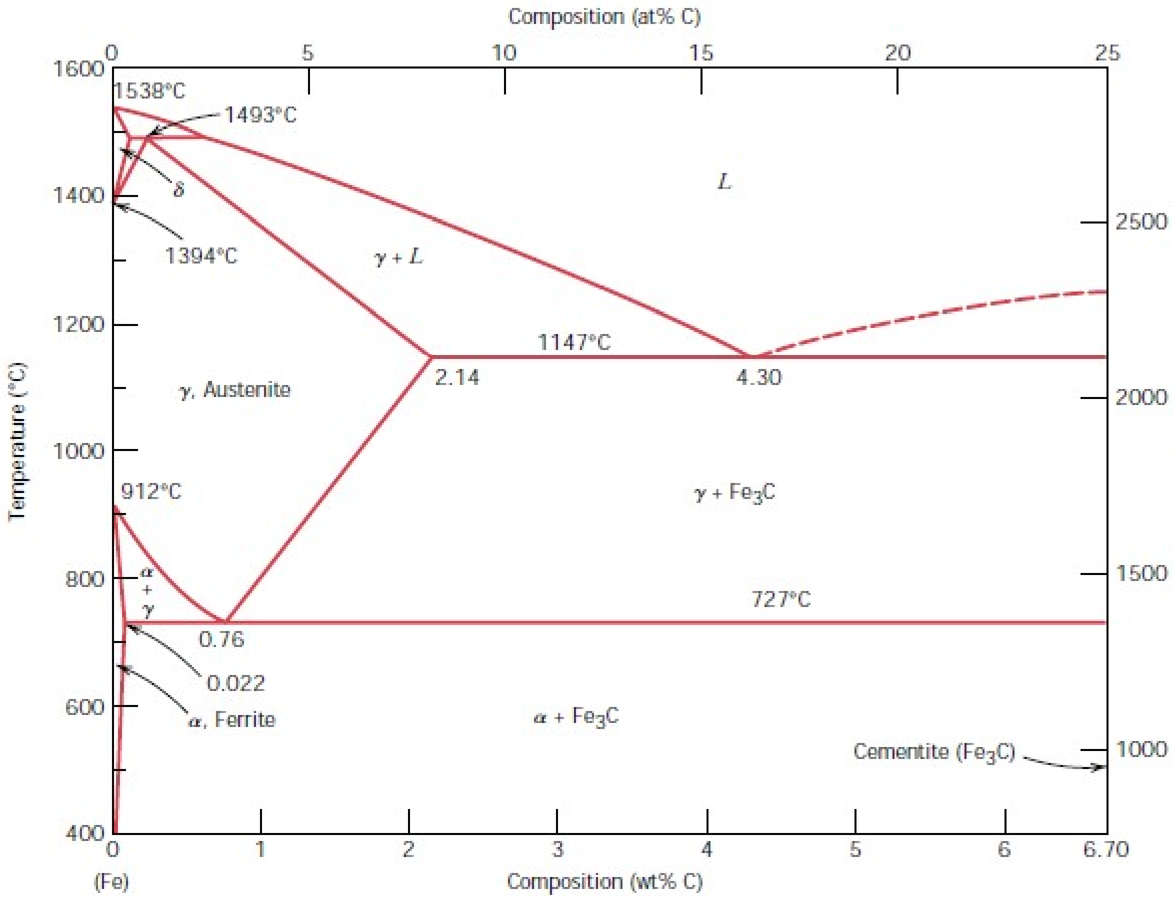
Heating and cooling curve of Pure-Fe



- Allotropy transformation occurs
  - Below equilibrium temperature during cooling
  - Above equilibrium temperature during heating

These temperature lags called as thermal hysteresis

Fe-Fe_3C Diagram



Invariant Reactions

- Eutectoid Reaction

$$\underset{(0.76\text{ wt\%C})}{\gamma} \overset{727^oC}{\longleftrightarrow} \underset{(0.022\text{wt.\%C})}{\alpha} + \underset{(6.67\text{wt.\%C})}{Fe_3C}$$

- Eutectic Reaction

$$\underset{(4.3\text{wt\%C})}{L} \overset{1147^oC}{\longleftrightarrow} \underset{(2.14\text{wt.\%C})}{\gamma} + \underset{(6.67\text{wt.\%C})}{Fe_3C}$$

- Peritectic Reaction

$$\underset{(0.53\text{wt\%C})}{L} + \underset{(0.09\text{wt.\%C})}{\delta} \overset{1493^oC}{\longleftrightarrow} \underset{(0.17\text{wt.\%C})}{\gamma}$$

Critical Temperatures in Fe-Fe_3C diagram

Notation

A_0 - Curie temperature of cementite

Magnetic cementite $\xrightarrow{210^oC}$ Non-magnetic cementite

A_1 – eutectoid transition temperature

γ-Fe $\xrightarrow{727^o}$ α-Fe + Fe_3C

A_2 – Curie temperature of Fe

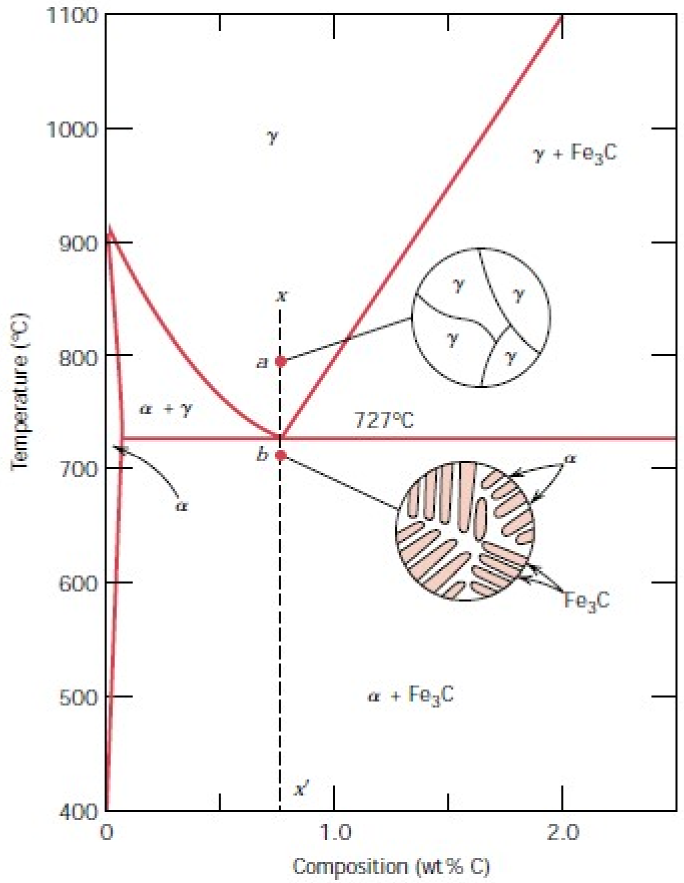
Ferromagnetic ferrite $\xrightarrow{768^oC}$ Paramagnetic ferrite

A_3 – the temp. at which ferrite just starts forming from austenite on cooling a hypoeutectoid steel

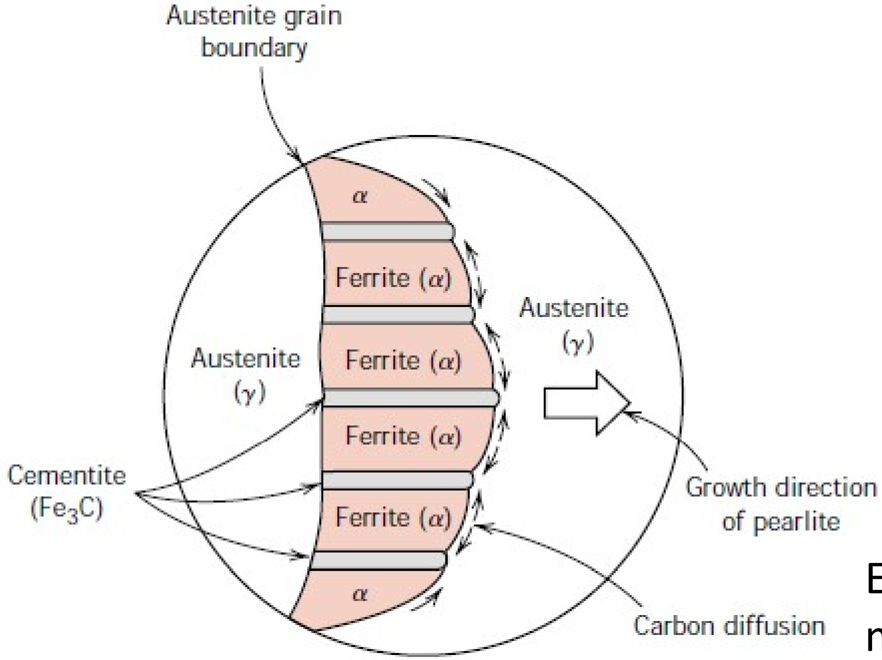
A_4 – the temp. at which δ-Ferrite starts forming from austenite on heating

Ac_m – the temp. at which cementite starts to forming from austenite on cooling a hypereutecoid steel

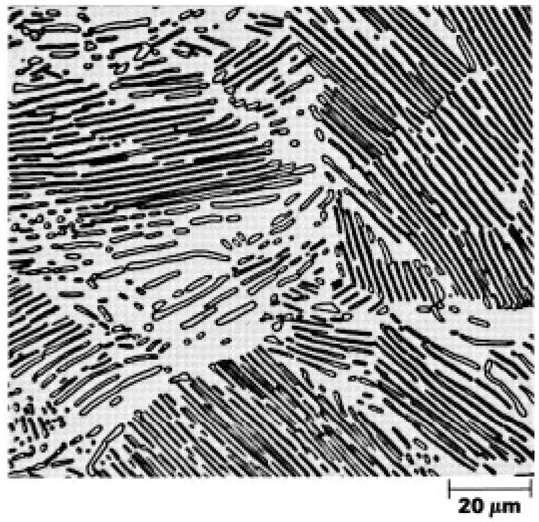
Eutectoid Transformation



Schematic representations of the microstructures for an iron–carbon alloy of eutectoid composition (0.76 wt% C) above and below the eutectoid temperature.



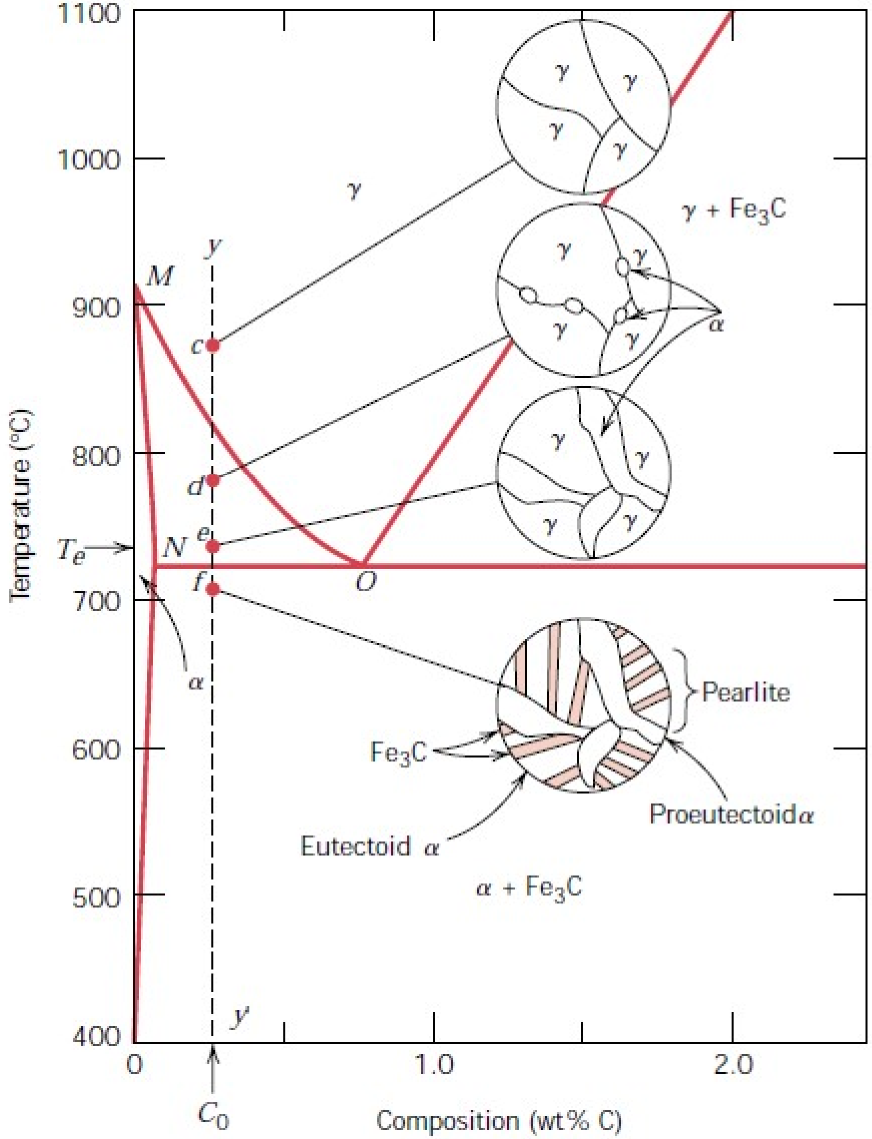
Schematic representation of the formation of pearlite from austenite; direction of carbon diffusion indicated by arrows.

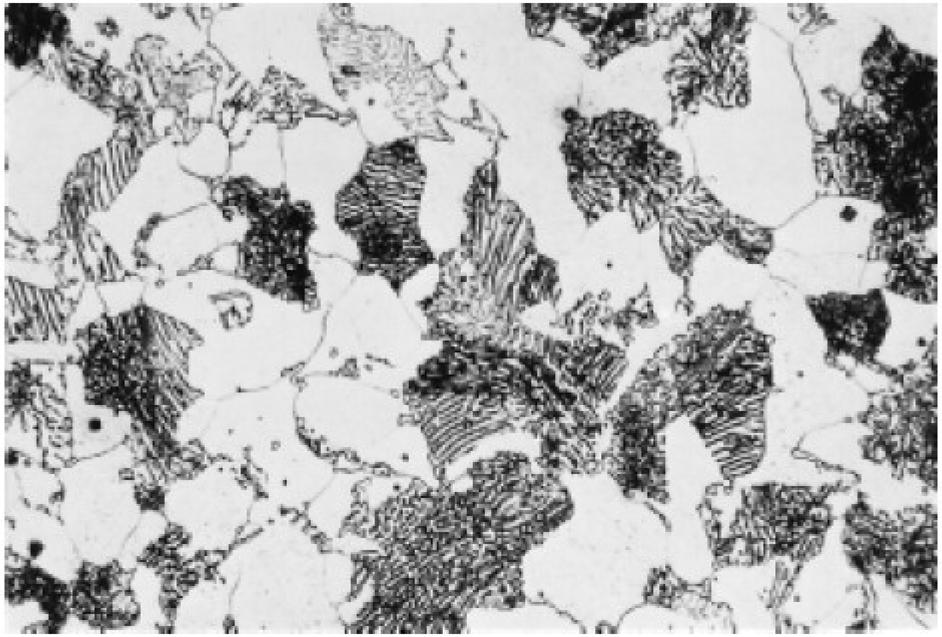


Eutectoid steel showing the pearlite microstructure consisting of alternating layers of ferrite (the light phase) and Fe_3C (thin layers most of which appear dark).

Hypo-eutectoid Transformation

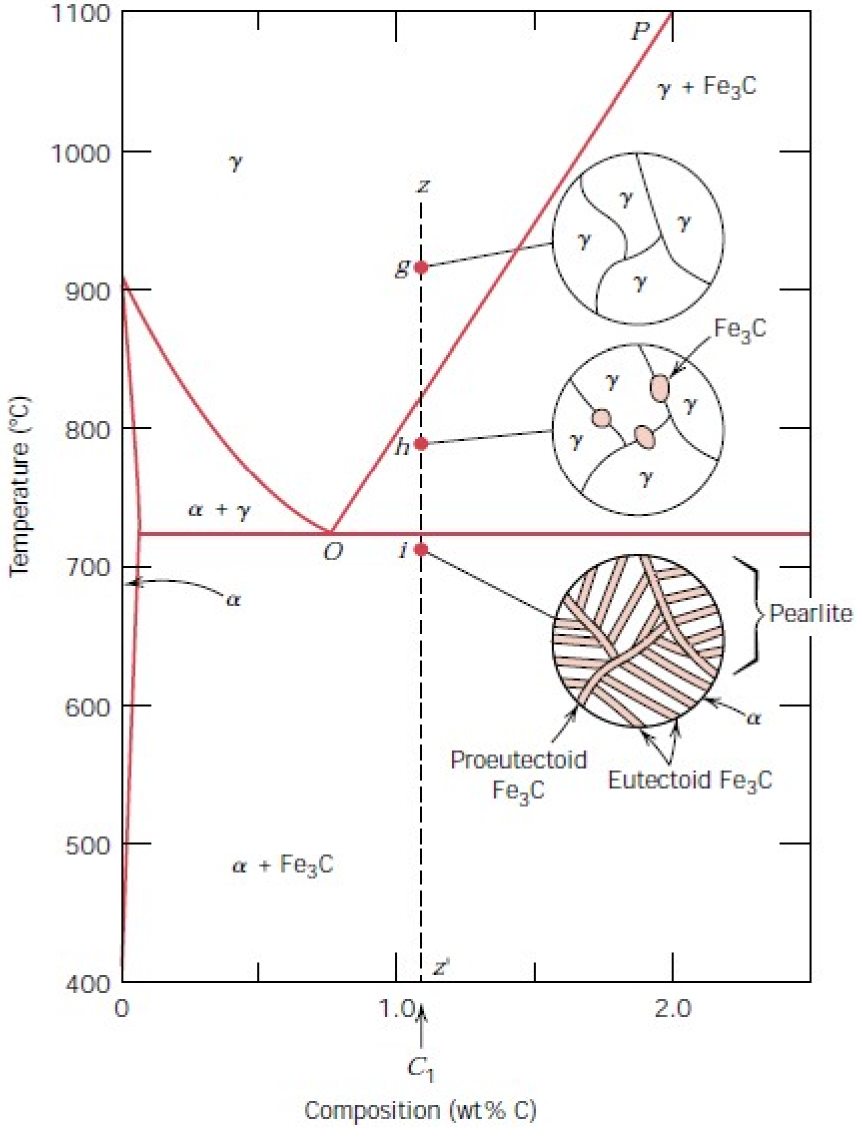
Schematic representations of the microstructures for an iron–carbon alloy of hypoeutectoid composition C_0 (containing less than 0.76 wt% C) as it is cooled from within the austenite phase region to below the eutectoid temperature.



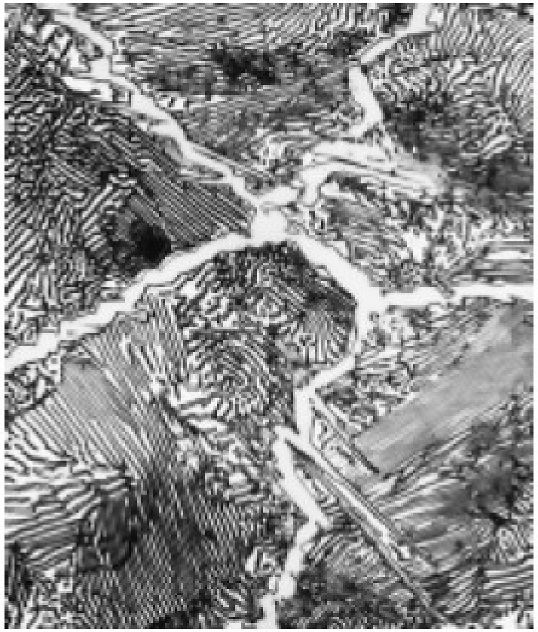


0.38 wt% C steel having a microstructure consisting of pearlite and proeutectoid ferrite.

Hyper-eutectoid Transformation



Schematic representations of the microstructures for an iron–carbon alloy of hypereutectoid composition C_1 *(containing between 0.76* and 2.14 wt% C), as it is cooled from within the austenite phase region to below the eutectoid temperature.



1.4 wt% C steel having a microstructure consisting of a white proeutectoid cementite network surrounding the pearlite colonies.

Effect of Alloying Elements in Steel

Alloying elements affects

- Relative stabilities of ferrite and austenite
- Critical temperatures (A_1, $A_{3,}$ A_4 and Ac_m)
- Carbon content

Types:

- Ferrite stabilizers
- Austenite stabilizers

Ferrite stabilizers

Elements which stabilizing ferrite phase are called ferrite stabilizers

- Ex.: Cr, W, Mo, V & Si

Ferrite stabilizers are,

- More soluble in α-Fe than γ-Fe
- Mostly in BCC crystal structure
- Decreases the amount of C in γ-Fe
- Reduces the austenite region in Fe-Fe_3C phase diagram by lowering A_4 & raising A_3.

Quantities of elements required for stabilization of ferrite:

Element	Cr	Si	W	Ti	Mo	V
Comp. (wt.%)	12.8	2.0	6	0.75	4	2

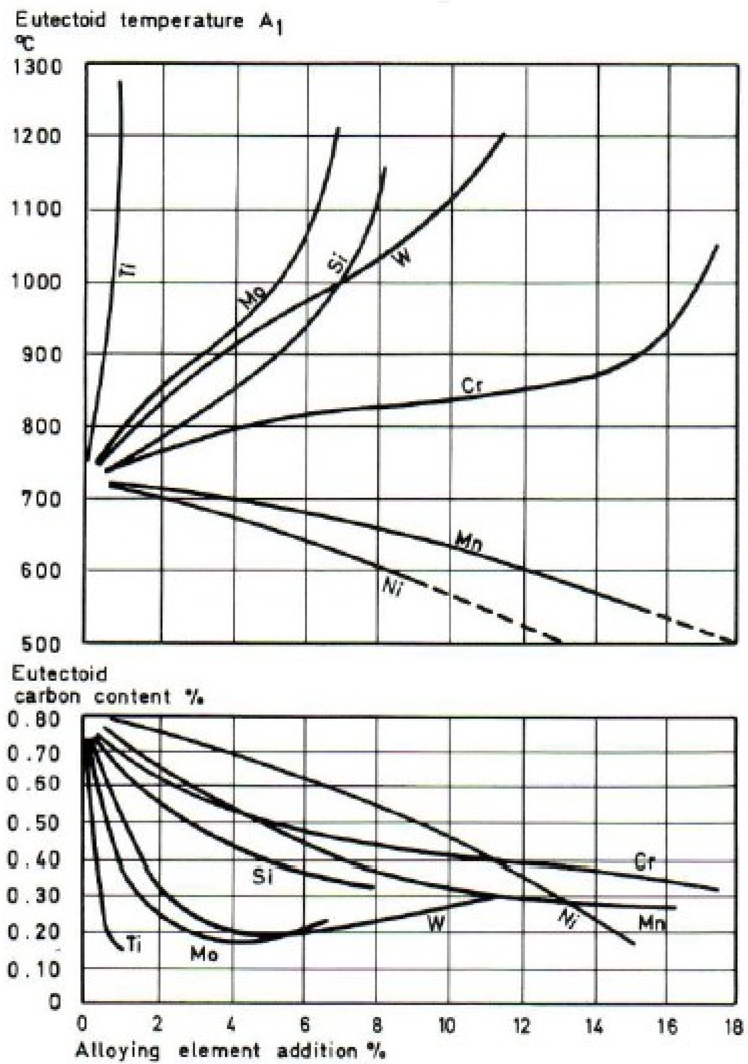
Austenite stabilizers

Elements which stabilizing austenite phase are called austenite stabilizers

Ex.: Ni, Mn

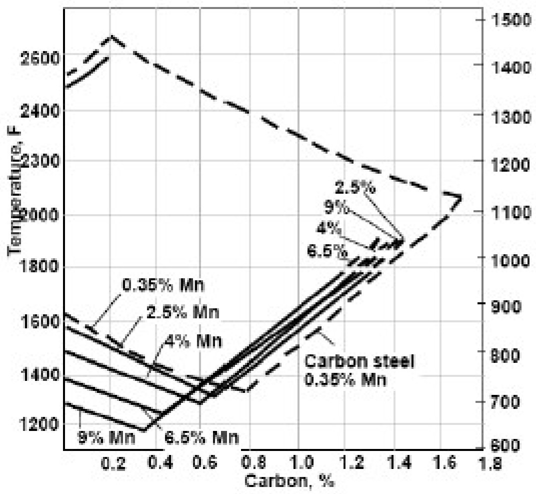
Austenite stabilizers are,

- More soluble in γ-Fe than α-Fe
- Mostly in FCC crystal structure
- Decreases the amount of C in α-Fe
- Enlarge the austenite region by shifting A_4 upward and A_3 & A_1 downwards. – even make austenite stable in room temp.

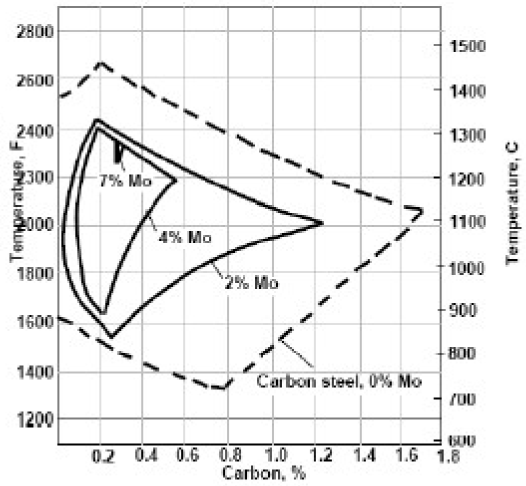


Influence of alloying element in eutecoid
Transformation temperature

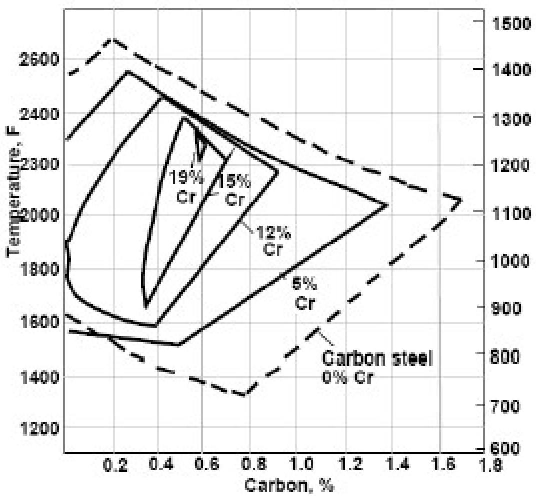
Influence of alloying element in gamma phase field.



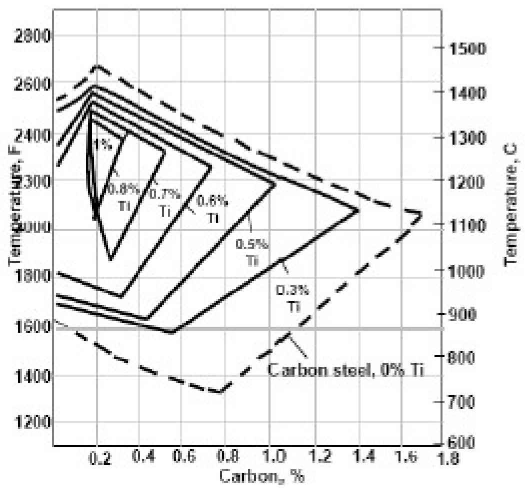
(a)



(b)



(c)



(d)

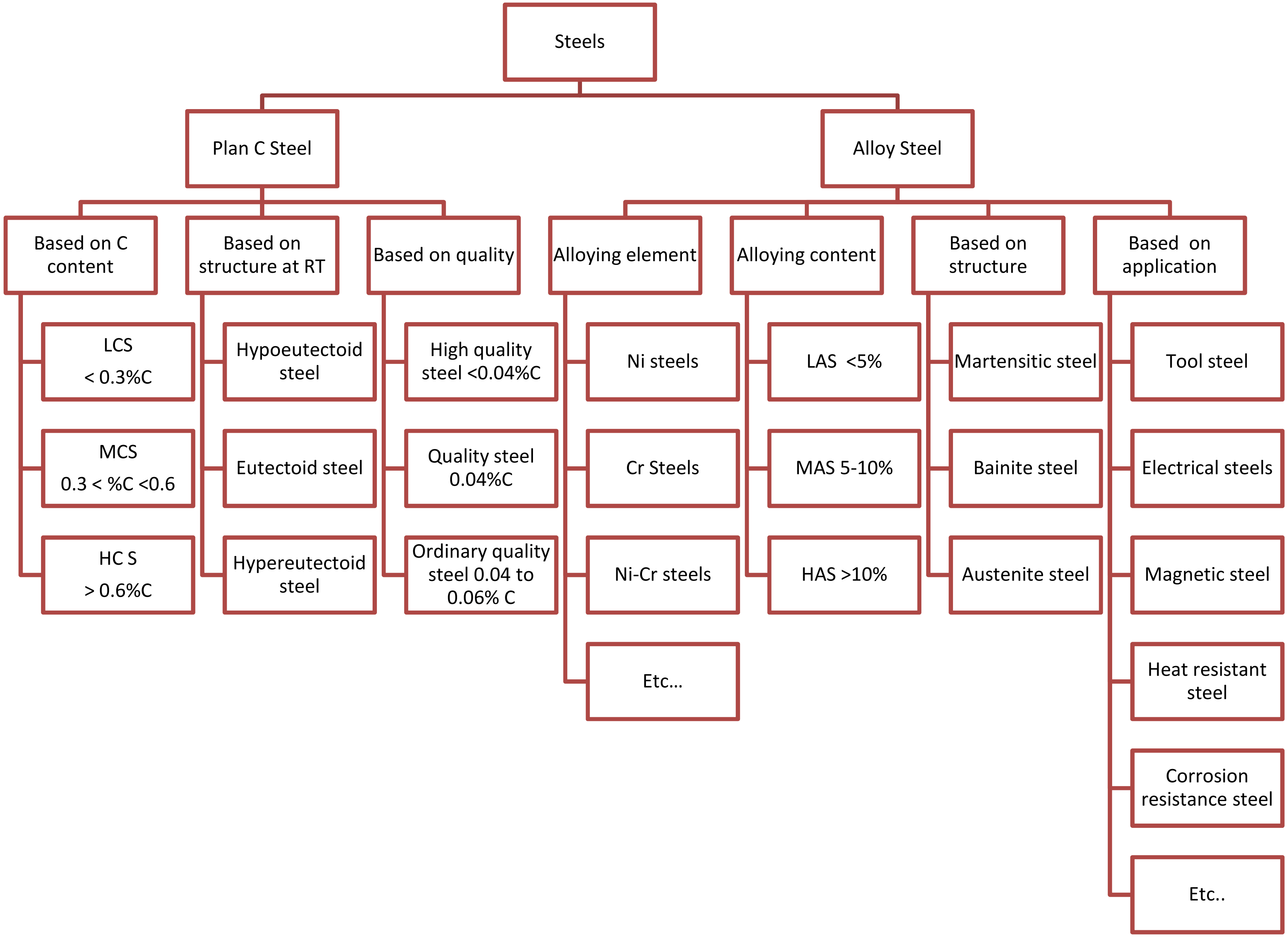
Carbon Equivalent (CE) is an empirical value in weight percent, relating the combined effects of different alloying elements used in the making of **carbon** steels to an **equivalent** amount of **carbon**. This value can be calculated using a mathematical equation.

Example: AWS states that for an equivalent carbon content above 0.40% there is a potential for cracking in the heat-affected zone (HAZ) on flame cut edges and welds.

$$CE = \%C + \left(\frac{\%Mn + \%Si}{6}\right) + \left(\frac{\%Cr + \%Mo + \%V}{5}\right) + \left(\frac{\%Cu + \%Ni}{15}\right)$$

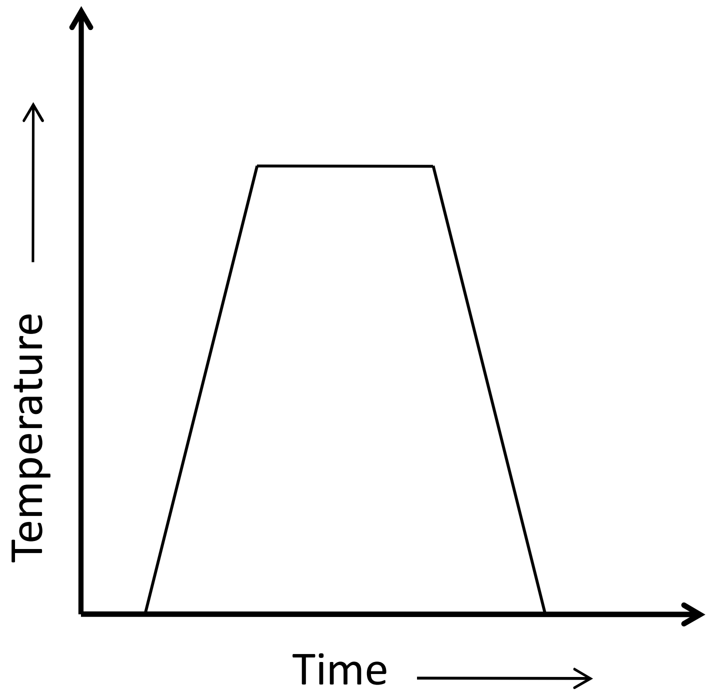
In high strength steels, CE = 0.5 which lead to cracking.

Classification of Steel



Heat Treatment

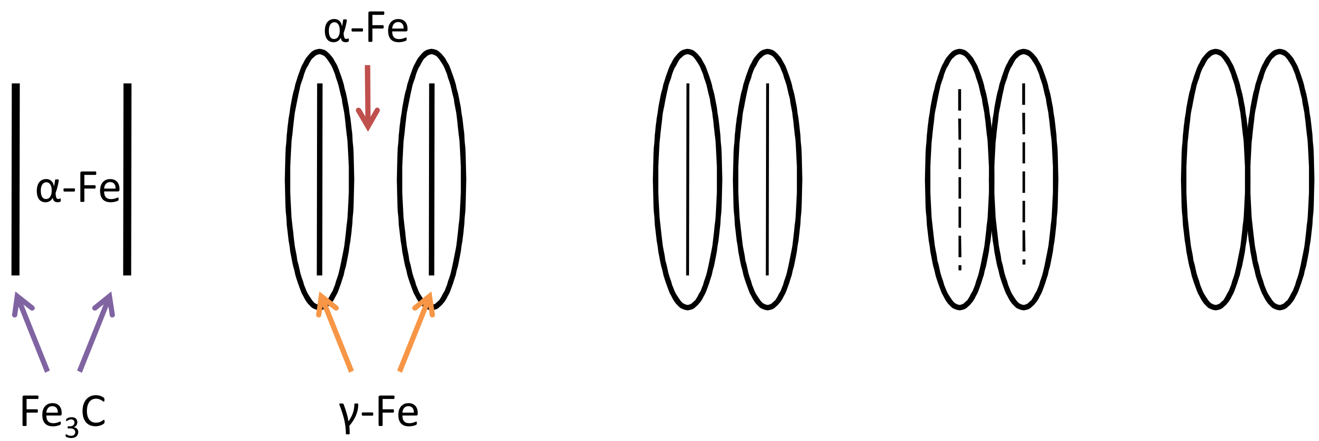
The heat treatment includes heating and cooling operations or the sequence of two or more such operations applied to any material in order to modify its metallurgical structure and alter its physical, mechanical and chemical properties.



Formation of Austenite on Heating

Eutectoid steel:

1. Upto 200^{o}C, C diffusion rate is insignificant
2. At 727^{o}C, α-Fe changes into γ-Fe.
3. The growth rate of austenite is higher than dissolution cementite into austenite.
4. Austenite formed at eutectoid temperature is not homogeneous



Hypo eutectoid and Hyper eutectoid steels:

1. These steels transformation into austenite different from eutectoid steel

2. In Hypoeutectoid steels, Fe_3C dissolves in to the ferrite which in turn transforms into austenite. Austenite nuclei form at ferrite grain boundary and then its grows.

3. In Hyper eutectoid steels, austenite grow by dissolving proeutectoid cementite

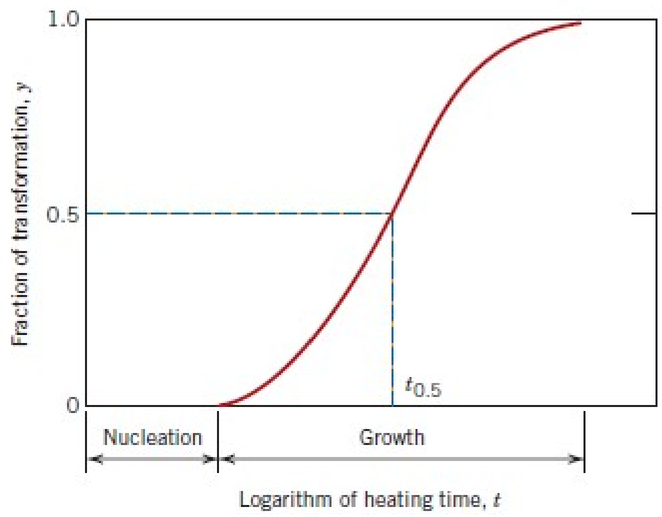
Kinetics of formation of austenite

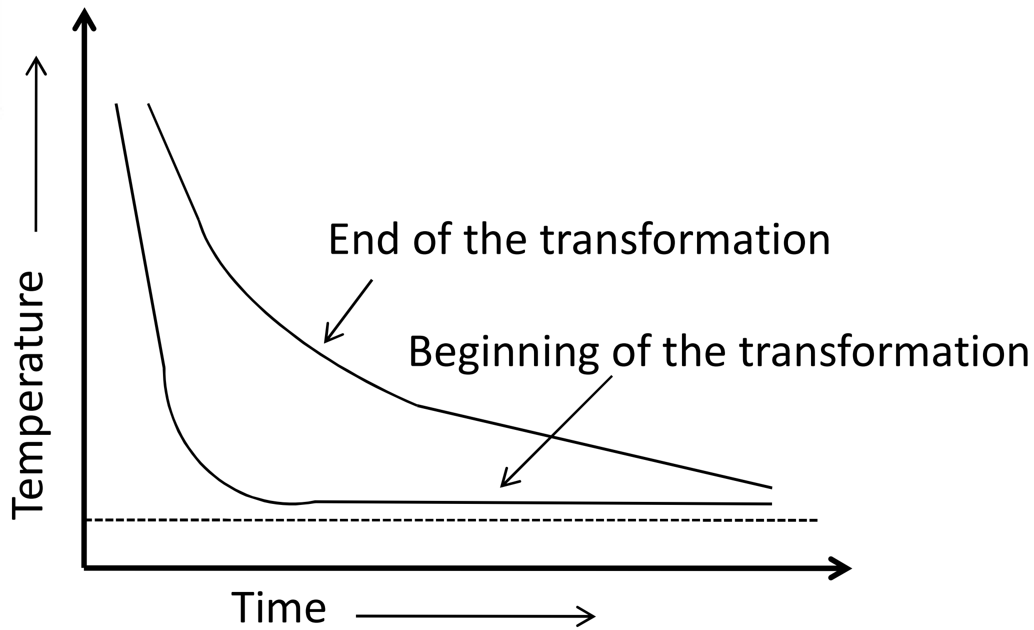
Heating eutectoid steel,

- Austenite formation take place by nucleation and growth
- Rate of nucleation or rate of growth or both → decides the kinetics of austenite formation

Factors

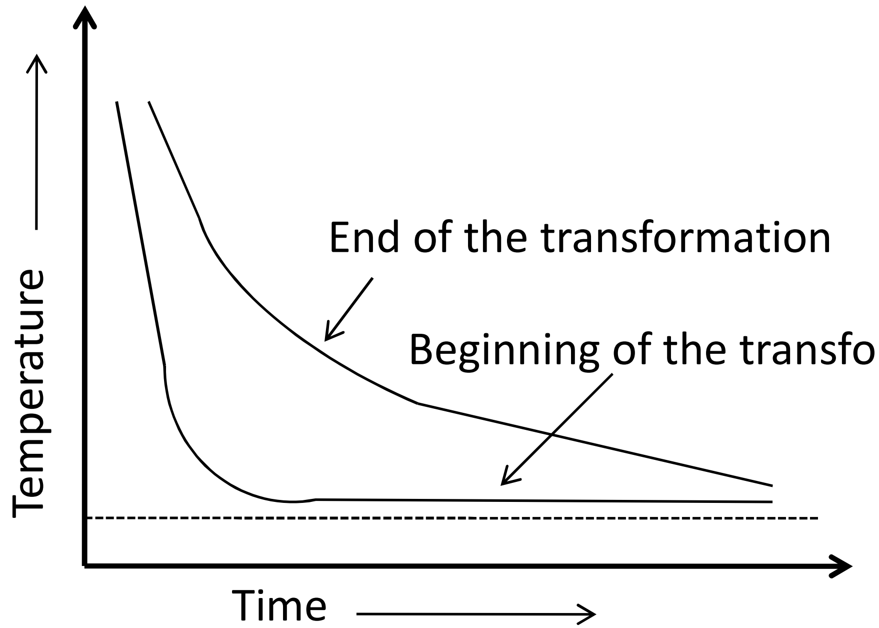
- The transformation temperature
- Holding time at transformation temperature
- Interface of ferrite and cementite





Effect of temperature on the time required for start and completion of transformation of pearlite to austenite

- Transformation completed short period in high temperature.
- For higher heating rates, nucleation starts at high temperature and vice versa.
- For all the heating rates, austenite formation taking place over a time period.



Effect of temperature on the time required for start and completion of transformation of pearlite to austenite

Isothermal Transformation

Fig. 1 : Salt bath I -austenitisation heat treatment. T =780^{o}C

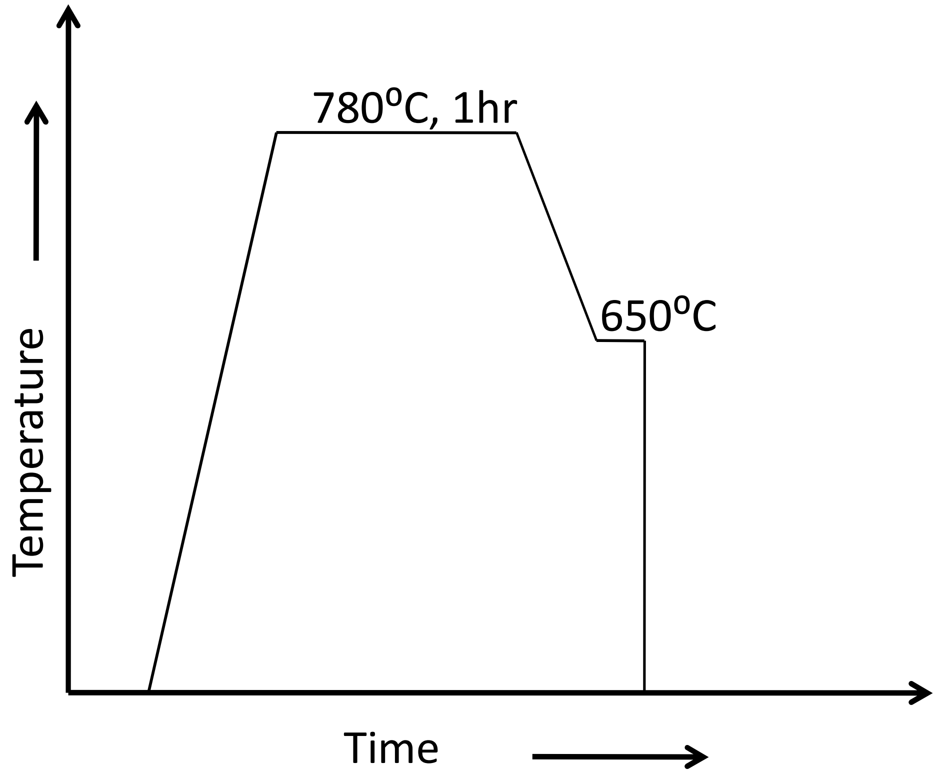
Fig. 2 : Bath II low-temperature salt-bath for isothermal treatment. T=650^{o}C

Isothermal Transformation

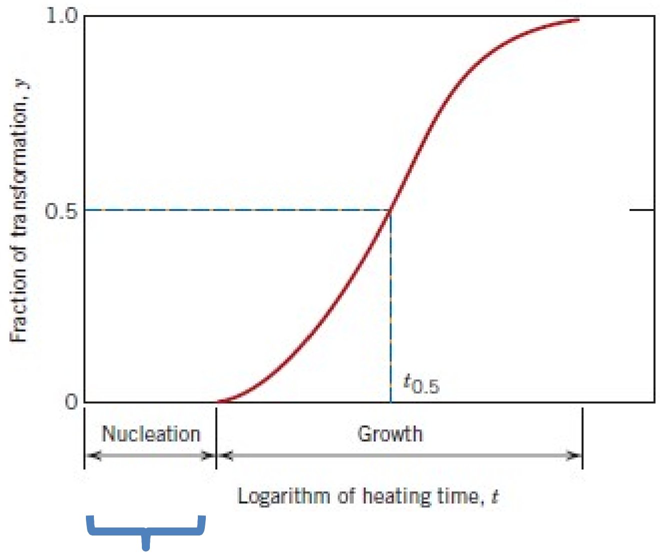
For eutectoid steel,

- In bath I, T=780^{o}C for ~ 1hr.
- Sample moved from bath I to bath II
- In bath II, at T=650°C.
- After specified time, the sample are removed and quenched in water.
- Study the microstructure of the sample using metallographic techniques

Repeat the experiment with varying time period in bath II

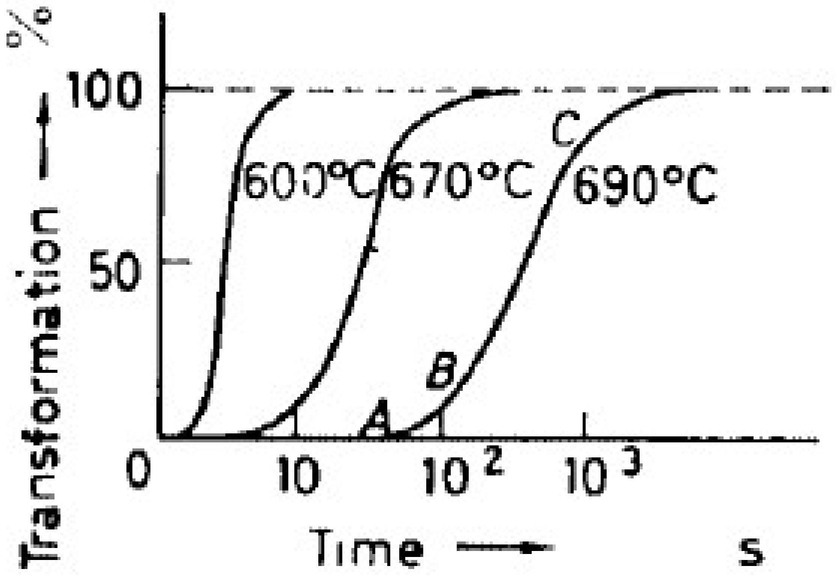


- Why 780^{o}C ?
- Why 1hr?
- Why 650^{o}C?
- What will happen if bath II temp. is 25^{o}C?

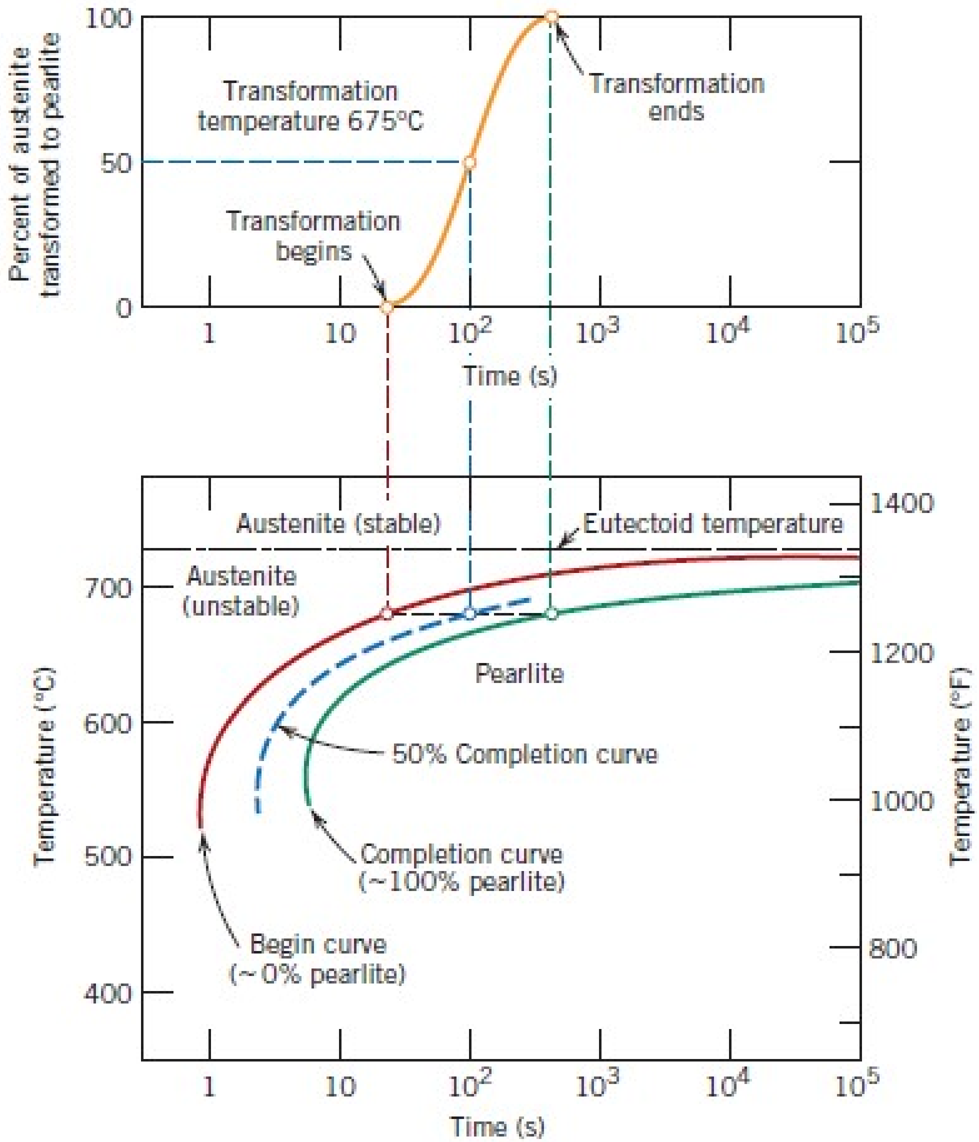


t - Incubation period

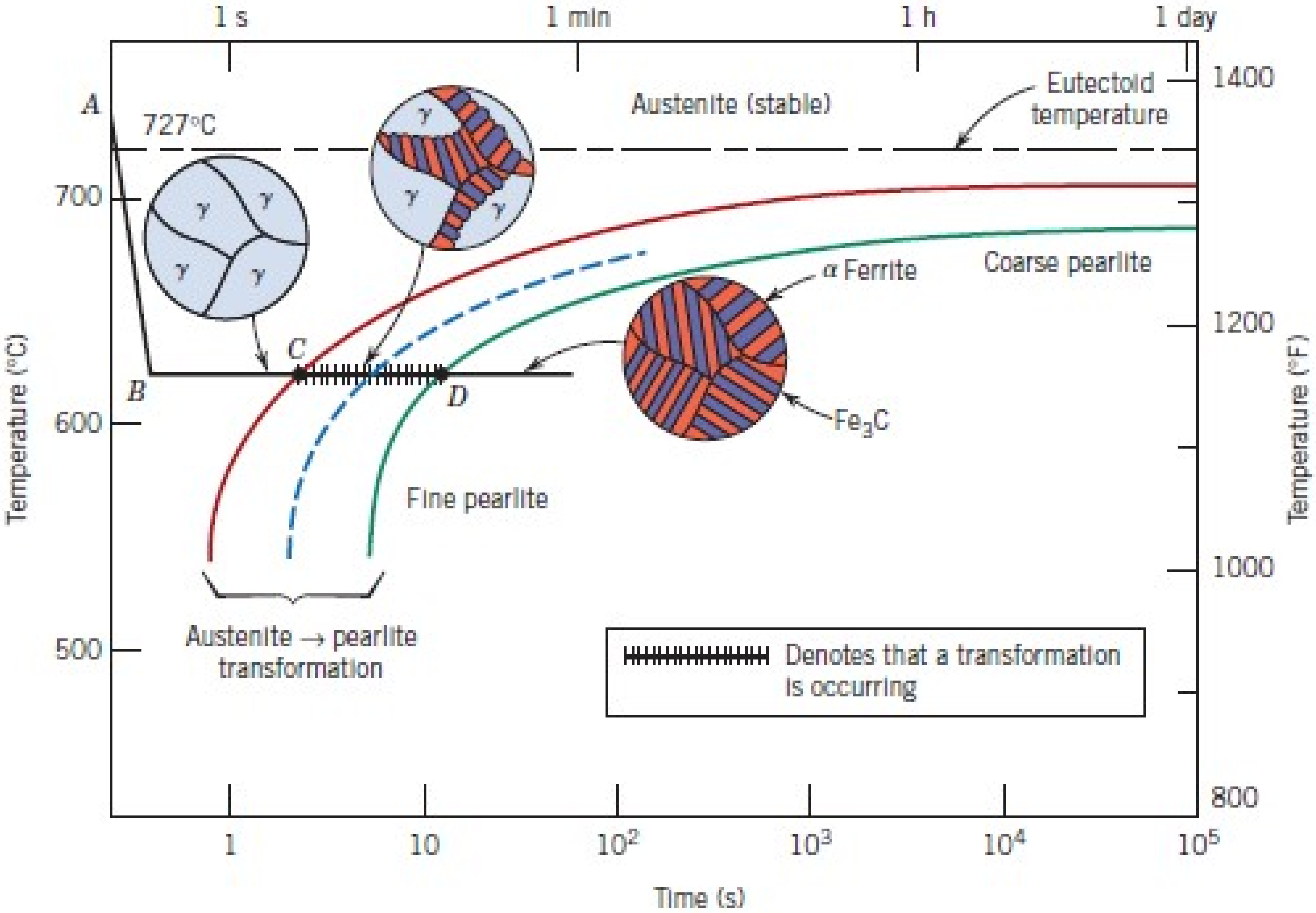
Isothermal Transformation curve
Or
C – Curve
Or
S - Curve



amount of pearlite formed with time



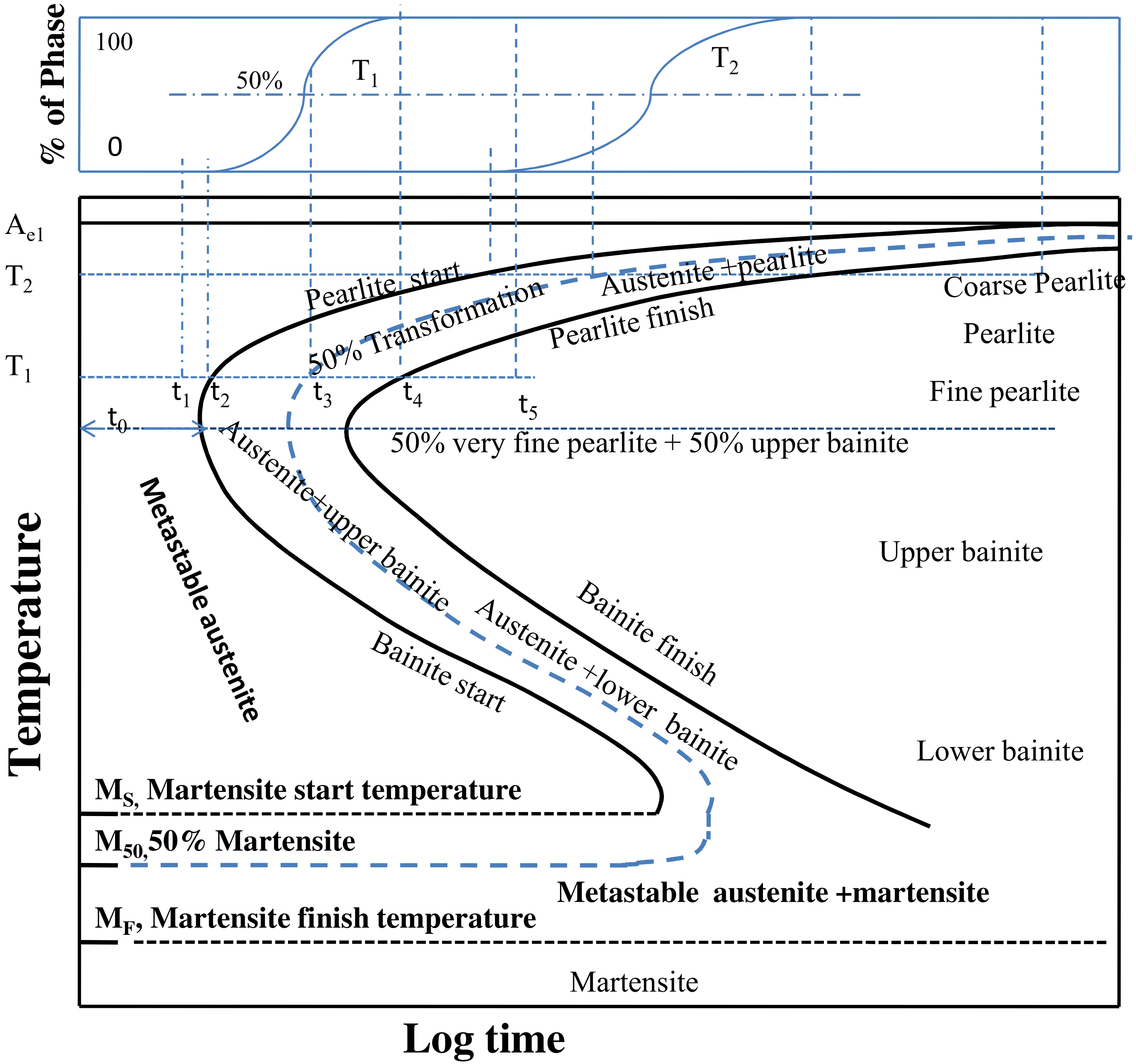
100
50
0
Percent of austenite transformed to pearlite
Transformation temperature 675°C
Transformation begins
Transformation ends
1
10
10^2
10^3
10^4
10^5
Time (s)
Austenite (stable)
Eutectoid temperature
Austenite (unstable)
Pearlite
50% Completion curve
Completion curve (~100% pearlite)
Begin curve (~ 0% pearlite)
700
600
500
400
Temperature (°C)
1400
1200
1000
800
Temperature (°F)
Time (s)



1 s
1 min
1 h
1 day
A
727°C
Austenite (stable)
Eutectoid temperature
700
600
500
1400
1200
1000
800
γ
α Ferrite
Coarse pearlite
C
B
D
Fe_3C
Fine pearlite
Austenite → pearlite transformation
Denotes that a transformation is occurring
Temperature (°C)
Temperature (°F)
1
10
10^2
10^3
10^4
10^5
Time (s)

Coarse pearlite   Fine pearlite

Figure: TTT Diagram for plain carbon eutectoid steel



At t_1, incubation period for pearlite, t_2, pearlite starting time

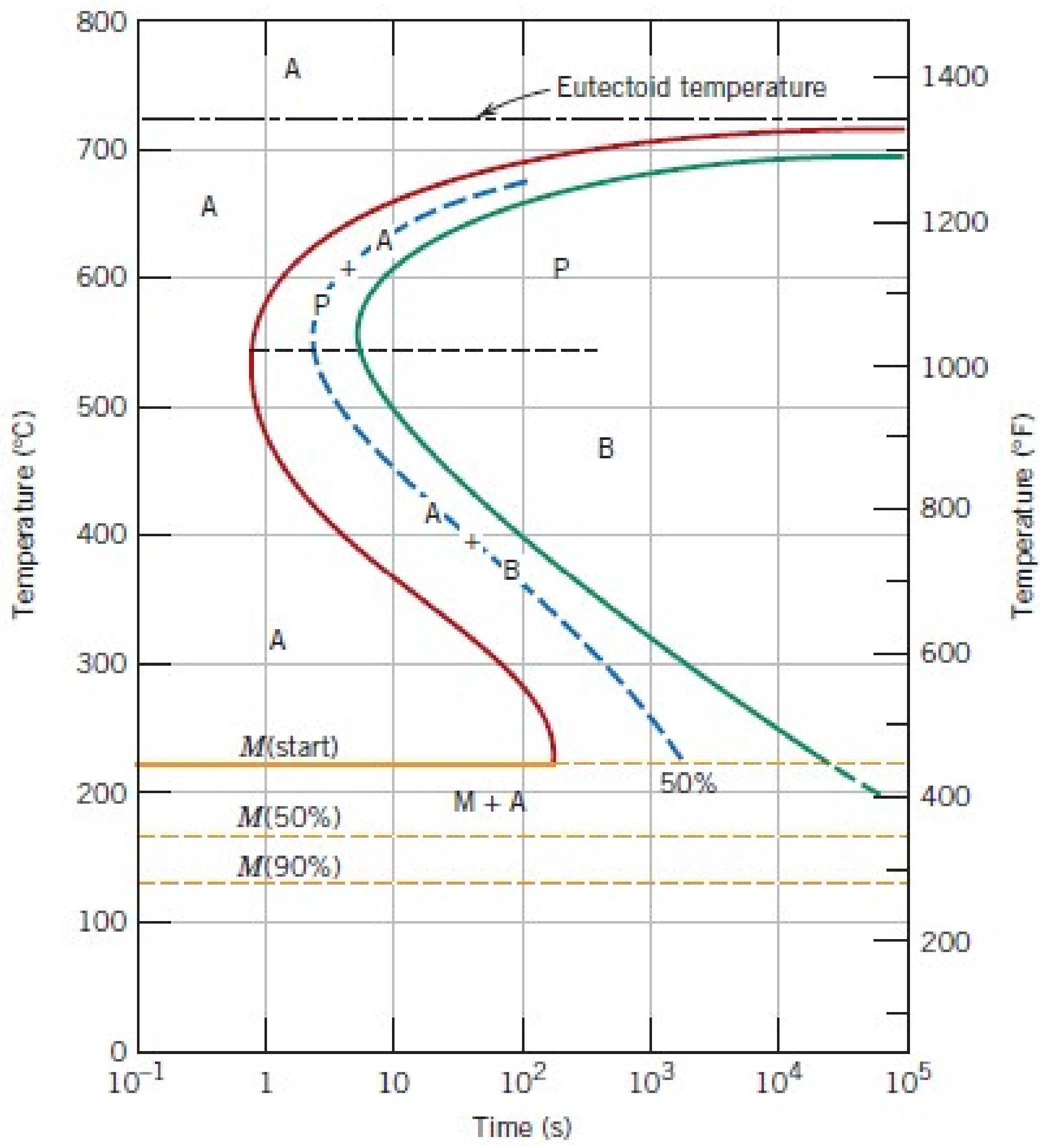
Pearlite finish time $=t_4$

Minimum incubation period t_0 at the nose of the TTT diagram,

M_S=Martensite start temperature

M_{50}=temperature for 50% martensite formation

M_F= martensite finish temperature



800
700
600
500
400
300
200
100
0
A
Eutectoid temperature
1400
1200
1000
800
600
400
200
A
A
+
P
P
B
A
+
B
A
M(start)
50%
M + A
M(50%)
M(90%)
Temperature (°C)
Temperature (°F)
10^{-1}
1
10
10^2
10^3
10^4
10^5
Time (s)

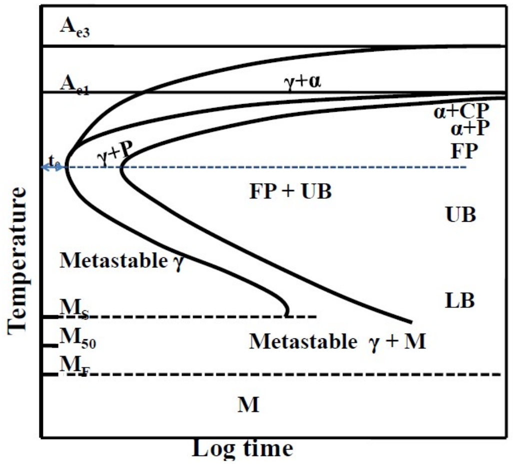
TTT diagrams for plain carbon hypoeutectoid, eutectoid and hypereutectoid steels

γ=austenite
α=ferrite
CP=coarse pearlite

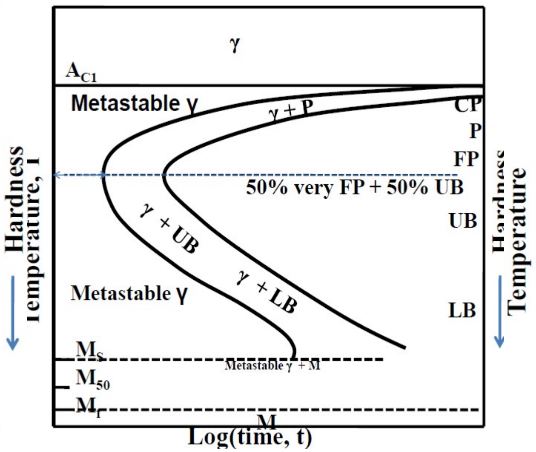
P=pearlite
FP=fine pearlite
UB=upper bainite
LB=lower bainite

M=martensite
M_S=Martensite start temperature
M_{50}=temperature for 50% martensite formation
M_F= martensite finish temperature

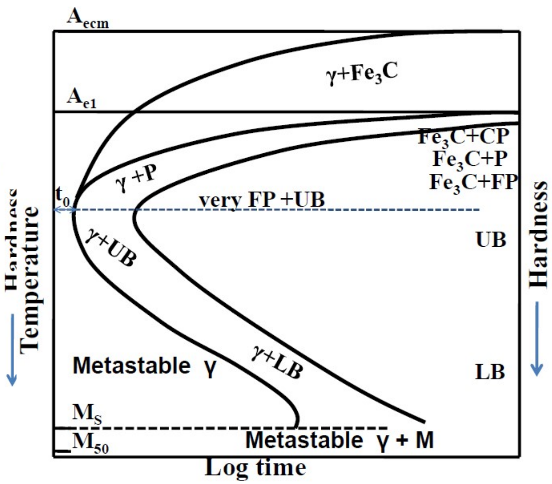
(a) TTT diagram for hypoeutectoid steel



(b) TTT diagram for eutectoid steel



(c) TTT diagram for hypereutectoid steel



Factors Affecting TTT Diagram

- Composition of steel
  - Amount of carbon and alloying elements
    - C or alloying element ↑es 'S' progressively lowered
    - M_s temperature decreases
  - Austenite stabilizers (Ni, Mn etc.) lower Ac_3 and Ac_1 temperatures too
  - Ferrite stabilisers (V, Mo, W, Cr etc) raise Ac3 and Ac1 temperatures and such steels show two 'C' curves (one for pearlite and other for bainite transformations)

- Carbon

Hypo eutectoid steel	**Hyper eutectoid steel**
Ferrite is the nucleating phase	Cementite is the nucleating phase
Nose of ‘S’ curve shift to left hand side	Nose of ‘S’ curve shift to left hand side

  - For bainite formation, ferrite is nuleating phase
  - If amount of C increases, the bainitic part of ‘S’ curve shits towards the right. i.e. bainitic transformation is uniformly retarded.

TTT Diagram for Alloy Steel

- Alloying Elements
  - Except Co all other alloying elements shift ‘S’ curve to the right
  - Carbide forming element which dissolved in austenite stabilize austenite phase which shift ‘S’ curve to the right.
    - The austenite phase tries to decompose to ferrite and alloyed carbide
    - Substitutional element diffusion is slow
    - Diffusion of C too slow, due to carbide forming elements
    - Reduce the allotropic change by solute drag effect on its interface boundary.

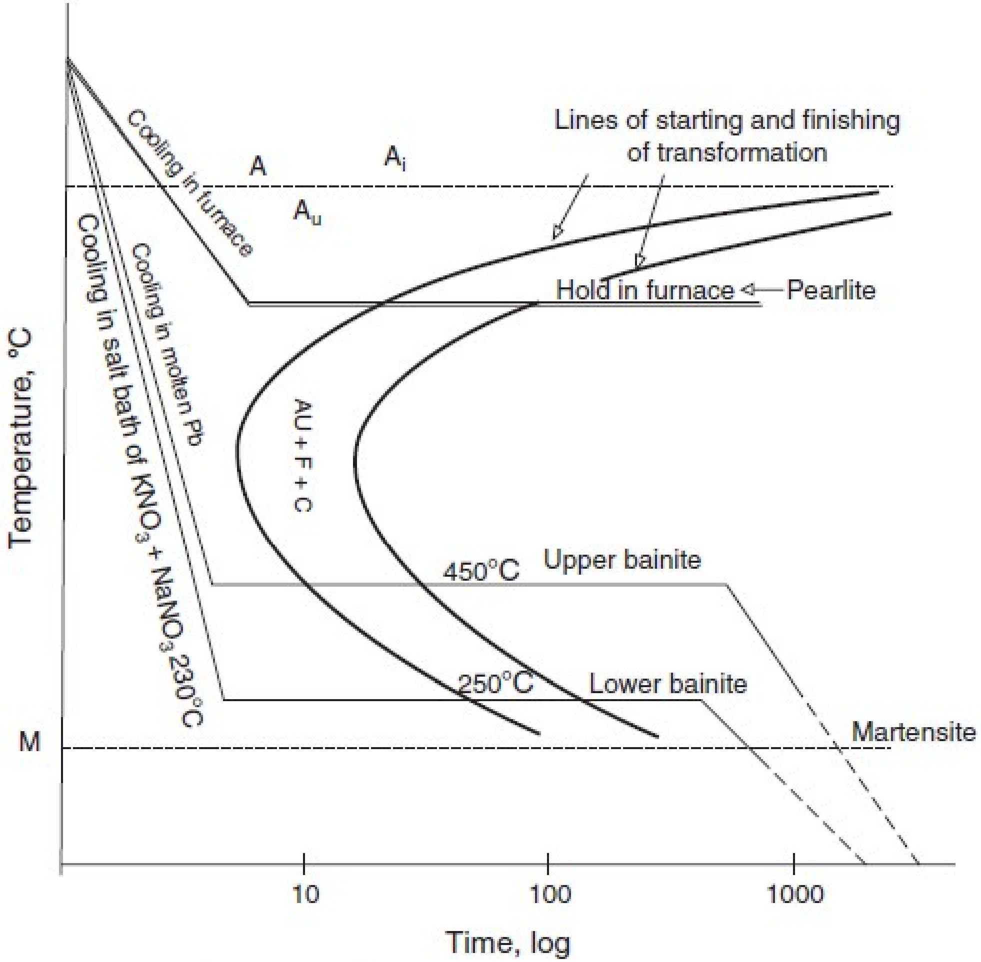
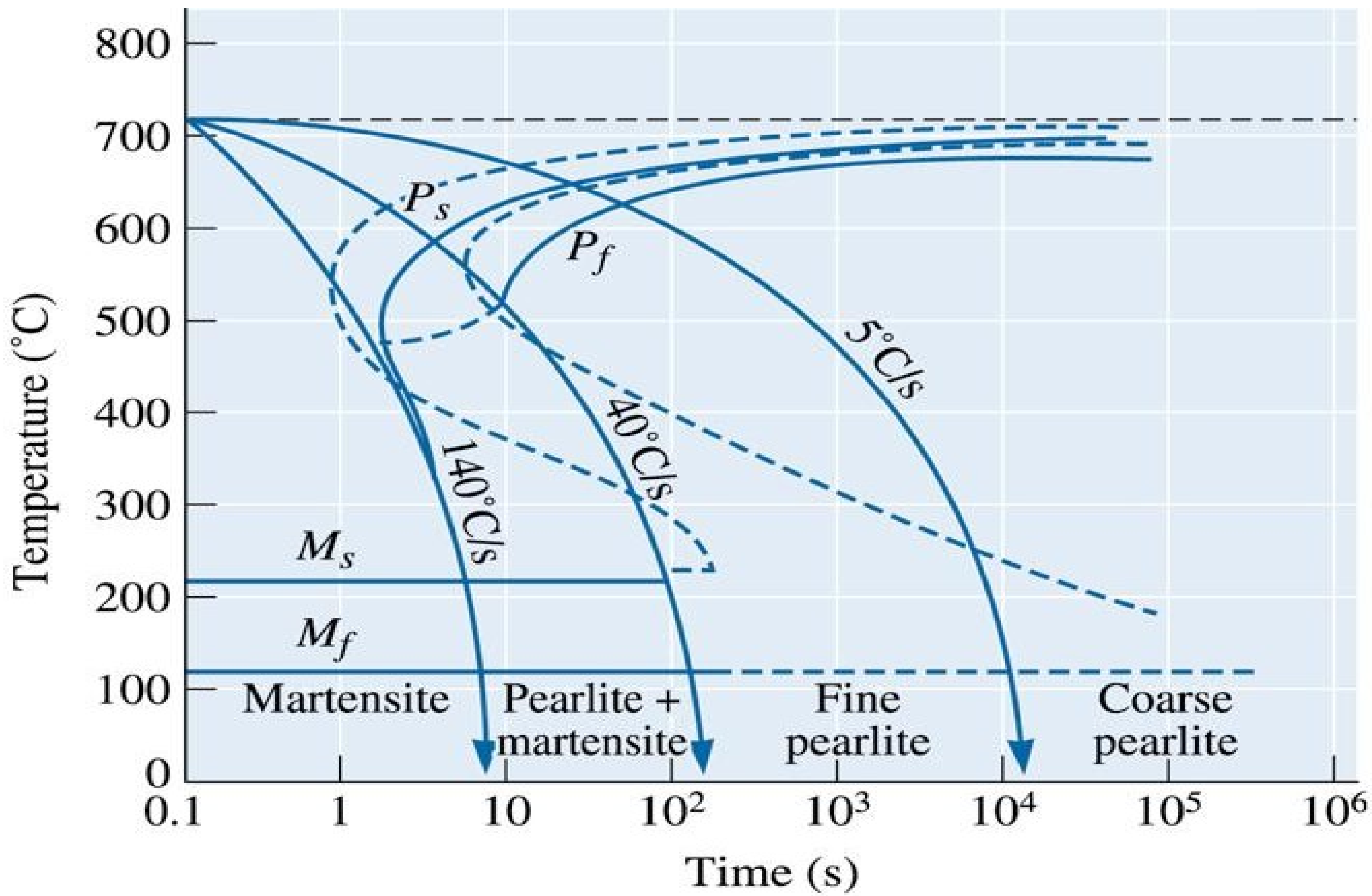
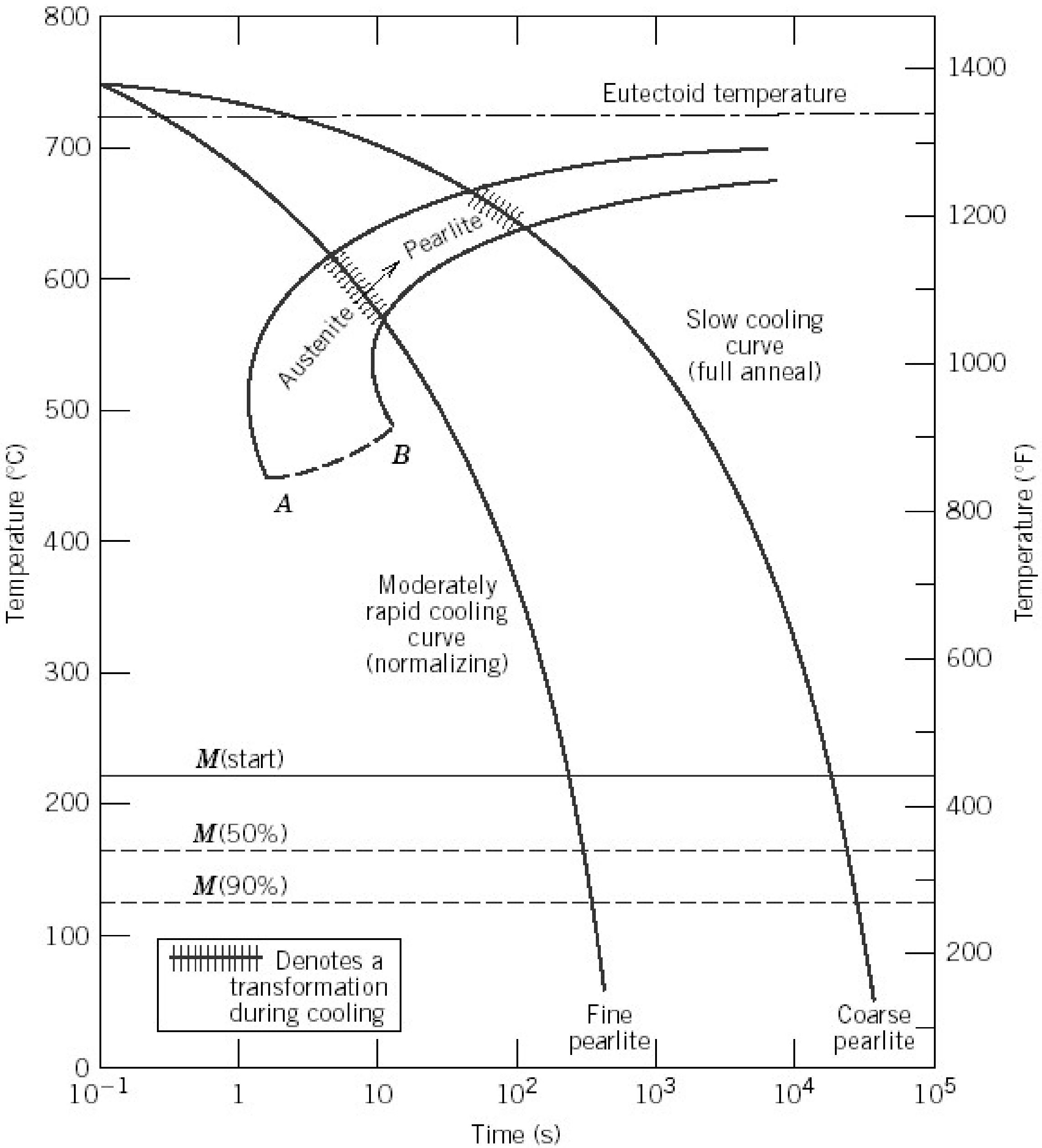


FIGURE 3.13 Isothermal transformation diagram for a eutectoid composition steel. A, stable austenite; A_u, undercooled austenite; F, ferrite; C, carbide.

Continuous Cooling Transformation Diagram



The CCT diagram (solid lines) for a 1080 steel compared with the TTT diagram (dashed lines).



800
700
600
500
400
300
200
100
0
1400
1200
1000
800
600
400
200
Temperature (°C)
Temperature (°F)
Eutectoid temperature
Pearlite
Austenite
Slow cooling
curve
(full anneal)
B
A
Moderately
rapid cooling
curve
(normalizing)
M(start)
M(50%)
M(90%)
Denotes a
transformation
during cooling
Fine
pearlite
Coarse
pearlite
10−1
1
10
10²
10³
10⁴
10⁵
Time (s)