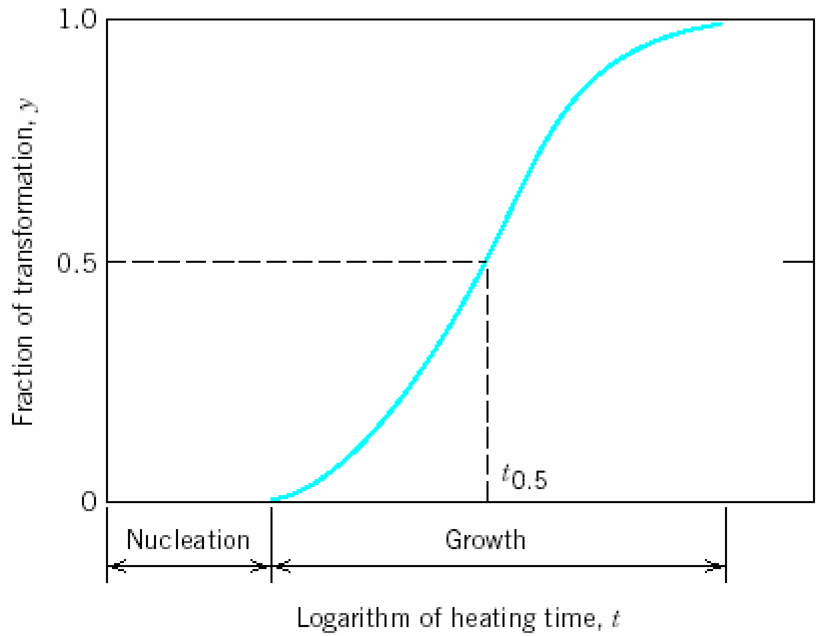
Phase Transformation in Metals



Phase transformation goes through two stages:

Stage 1: Nucleation (formation of very small particles of the new phase, which are capable of growing.

Stage 2: Growth (nuclei increase in size on the expense of the parent phase.

FRACTION OF TRANSFORMATION

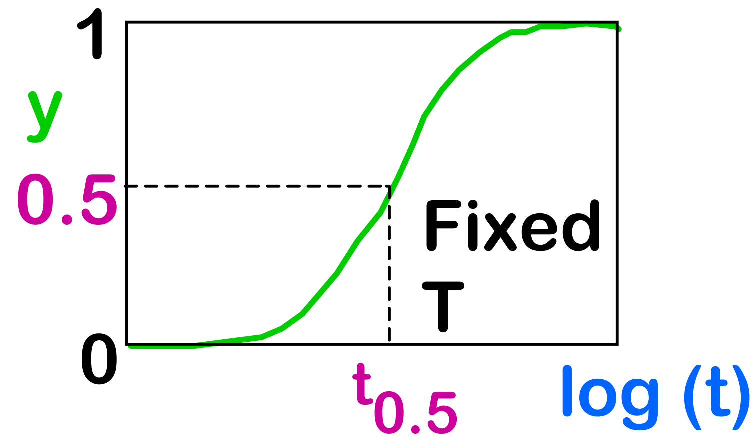
- **Fraction transformed depends on time.**

Avrami Eqn.

$$y = 1 - e^{-kt^n}$$

fraction transformed → y

time → t



K, n are time independent constants.

- **Transformation rate depends on T.**

activation energy → Q

$$r = \frac{1}{t_{0.5}} = Ae^{-Q/RT}$$

R: gas constant

T: Absolute temp.

Q: Activation energy for a particular reaction

A: Constant

Rate of transformation is defined as the reciprocal of the time required for the transformation to proceed half way to completion.

TRANSFORMATIONS & UNDERCOOLING

Eutectoid reaction: at 0.76wt% C and temp.: 727 C

$$\gamma\ (0.76\text{wt\%C}) \rightarrow \alpha\ (0.022\ \text{wt\%C}) + Fe_3C\ (6.7\ \text{wt\%C})$$

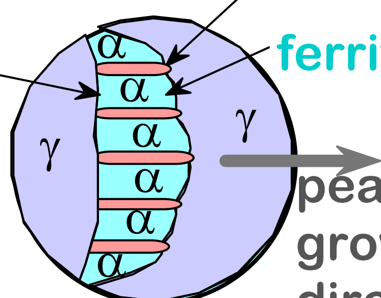
Pearlite

- **Growth of pearlite from austenite:**

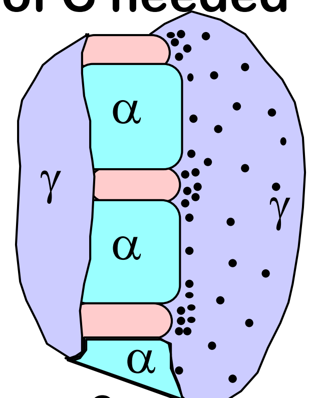
Austenite (γ) grain boundary

cementite (Fe_3C)

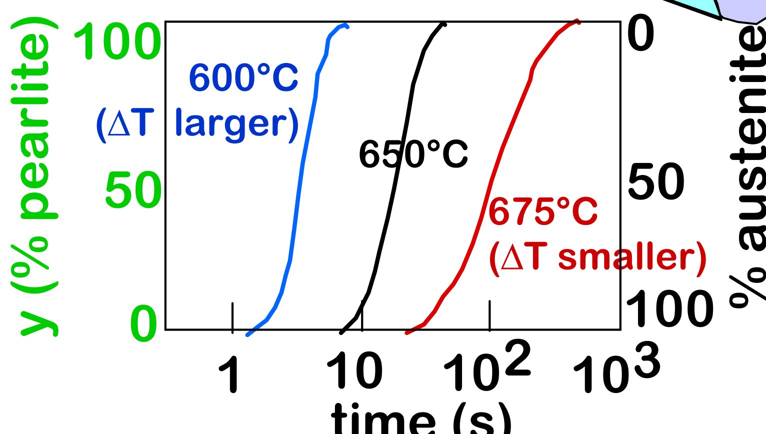
ferrite (α)



Diffusive flow of C needed

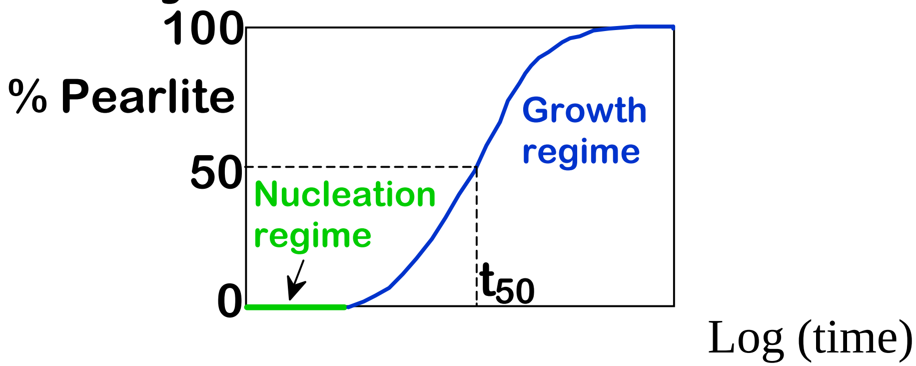


- **Reaction rate increases with ΔT (more under cooling results in more nucleation rate)**

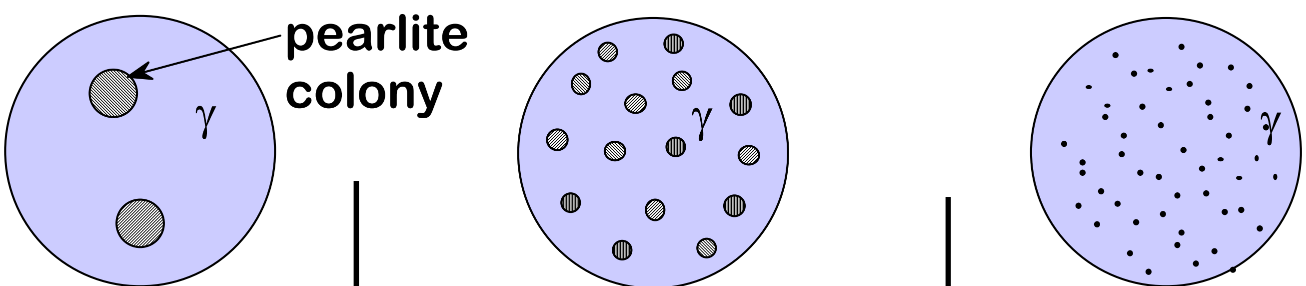


NUCLEATION AND GROWTH

- **Reaction rate is a result of nucleation and growth of crystals.**



- **Examples:**



T just below T_E
Nucleation rate low
Growth rate high

T moderately below T_E
Nucleation rate med .
Growth rate med.

T way below T_E
Nucleation rate high
Growth rate low

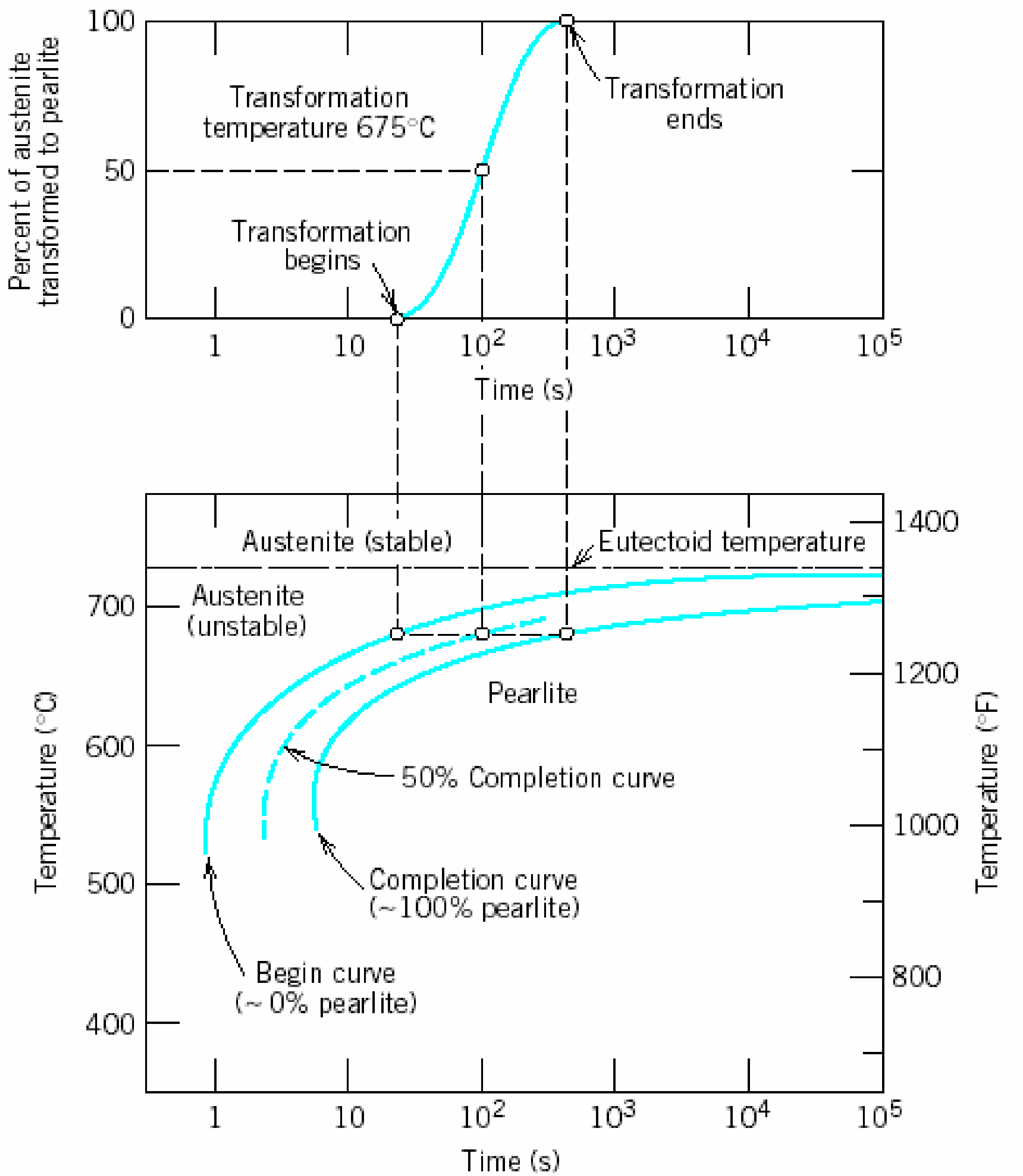
Isothermal Transformation Diagrams (TTT Diagram, Time – Temp.-Transformation)

NOTE:

•Just below the eutectoid temp. (small ΔT = small degree of under cooling) long times of the order 10^5 s needed for 50% transformation and therefore the reaction rate is very slow.

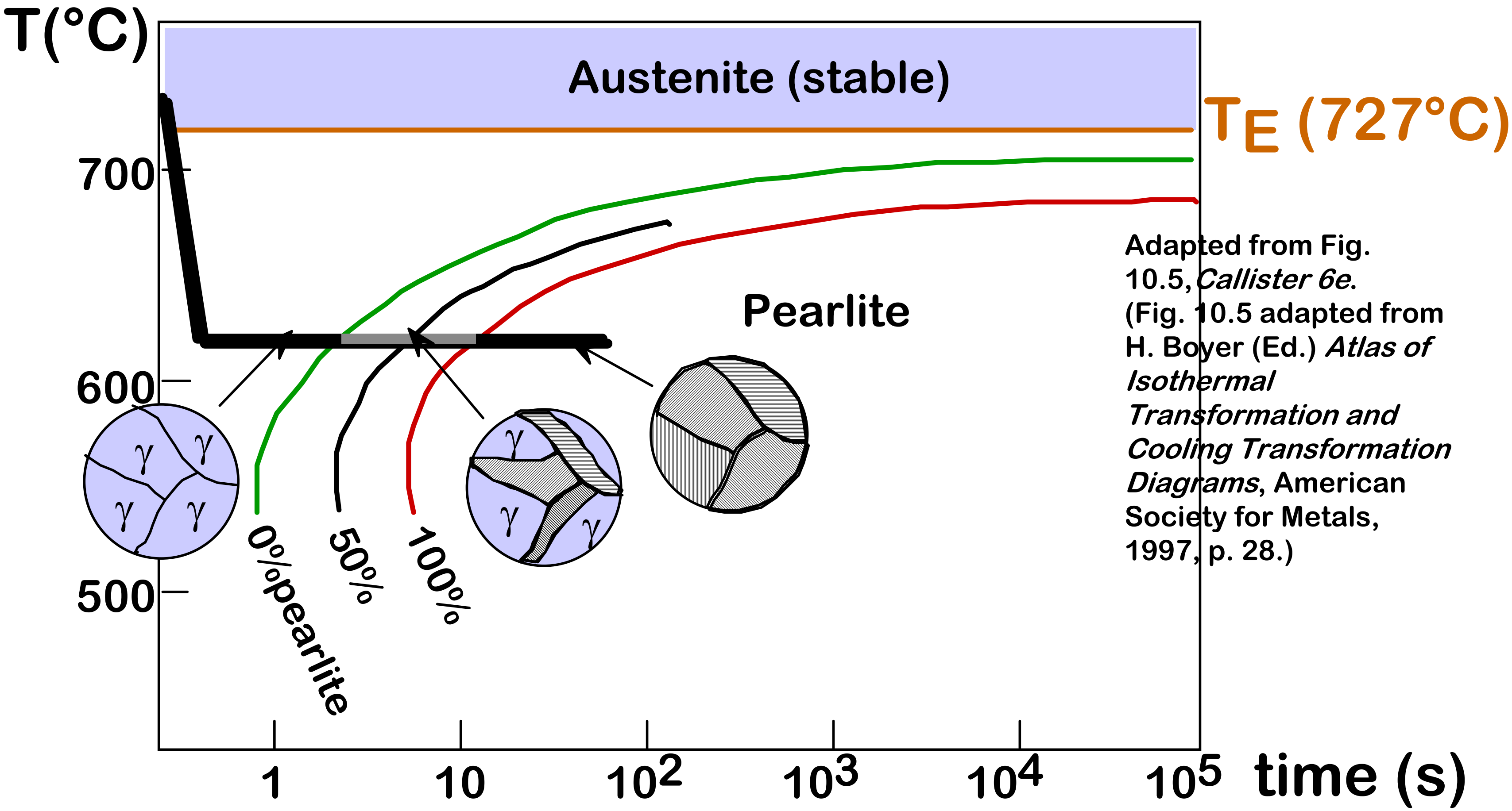
•For large degree of under cooling the time for 50 % transformation is short and thus the reaction rate is high.

•This plot is valid only for eutectoid composition.



EX: COOLING HISTORY Fe-C SYSTEM

- **Eutectoid composition, C_o = 0.77wt%C**
- **Begin at T > 727C**
- **Rapidly cool to 625C and hold isothermally.**

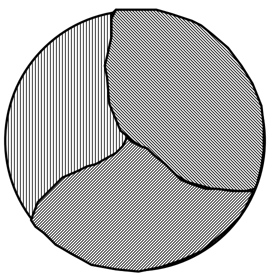


Adapted from Fig. 10.5, *Callister 6e*. (Fig. 10.5 adapted from H. Boyer (Ed.) *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, 1997, p. 28.)

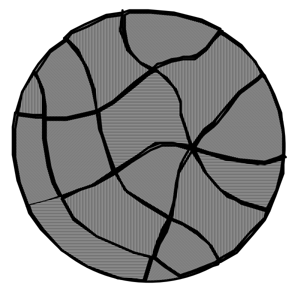
- At temperatures just below the eutectoid temperature, relatively thick layers of α and fe_3c phases are produced; this microstructure is termed coarse pearlite.

- At temperatures around 540 (540-600) C thin layered structure is produced termed fine pearlite

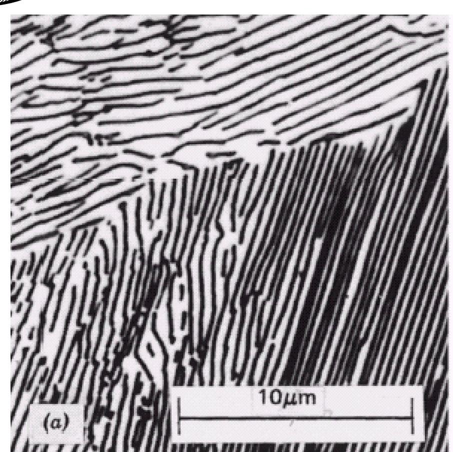
- Pearlite forms above the nose of the curve; in the temperature range of 540C to 727 C



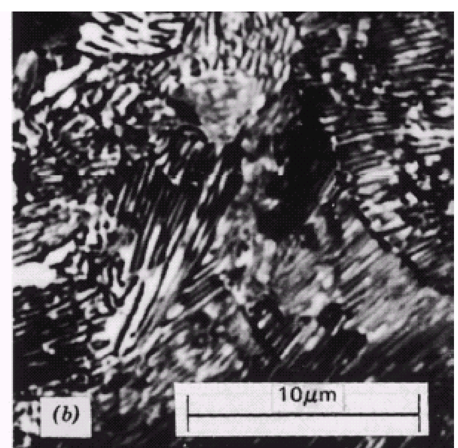
- Smaller ΔT: colonies are larger



- Larger ΔT: colonies are smaller

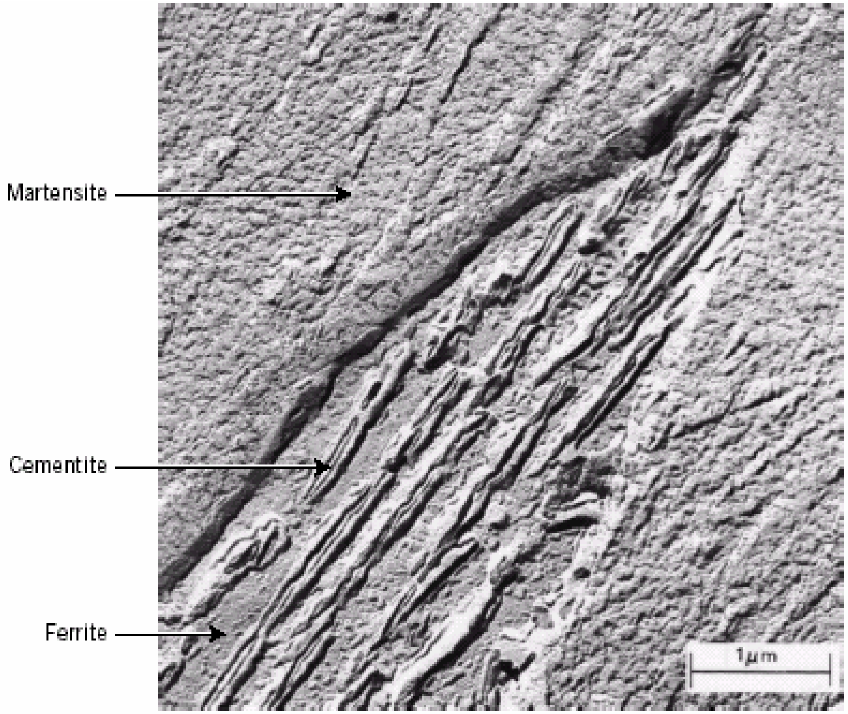


Coarse pearlite

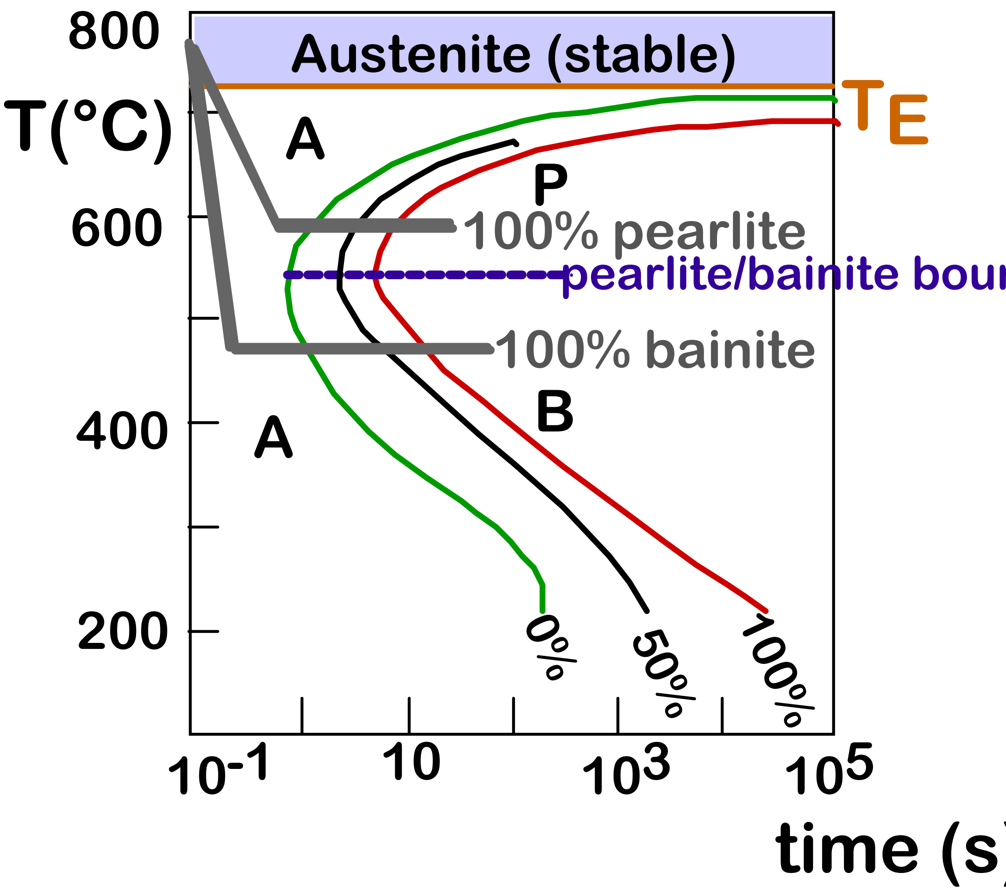


fine pearlite

•Bainite Forms in the range of temperatures from 215 C to 540 C. The microstructure of bainite consist of ferrite and cementite



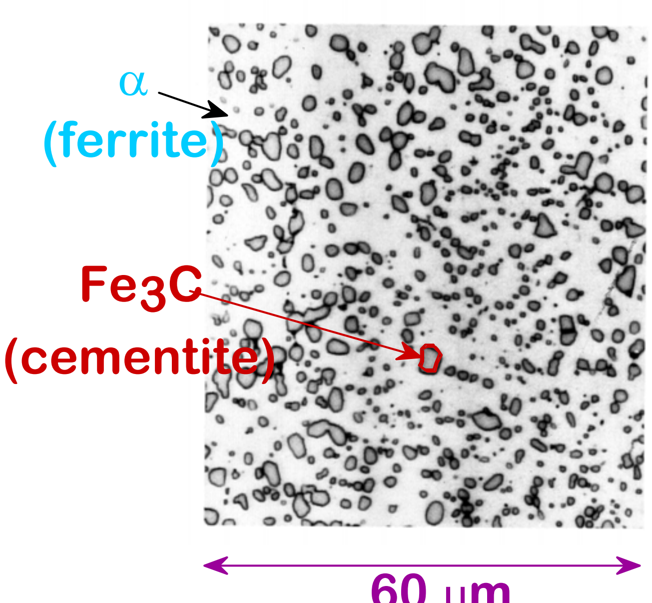
Elongated fe_3c particles in needles of ferrite



N.B. Once some portion of the alloy transformed to pearlite or bainite, other transformations is not possible with out reheating to form austenite.

OTHER PRODUCTS: Fe-C
Spheroidite

If a steel alloy having either pearlitic or bainitic microstructures is heated to and left at a temperature below the eutectoid temp (727 C) for long period of time for example at 700 C for 18-24 hours the microstructure achieved is shperoidite. Fe3c phase appears as sphere – like particles embedded in a continuous α phase matrix.



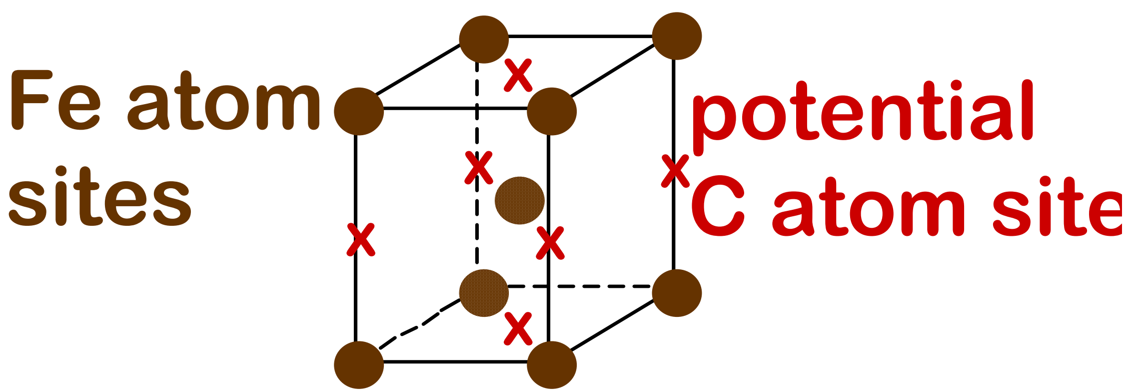
OTHER PRODUCTS: Fe-C
Martensite

- **Martensite:**
  --γ(FCC) to Martensite (BCT)

•Martensite is formed when austenitized iron-carbon alloys are rapidly cooled or quenched to relatively low temperatures.

•Martensite is a non-equilibrium single phase structure that results from diffusionless transformation of austenite.

•Martensite occurs when the quenching rate is high enough to prevent diffusion of carbon, so carbon atoms are trapped as interstitial impurities in body centered tetragonal (BCT) martensite.

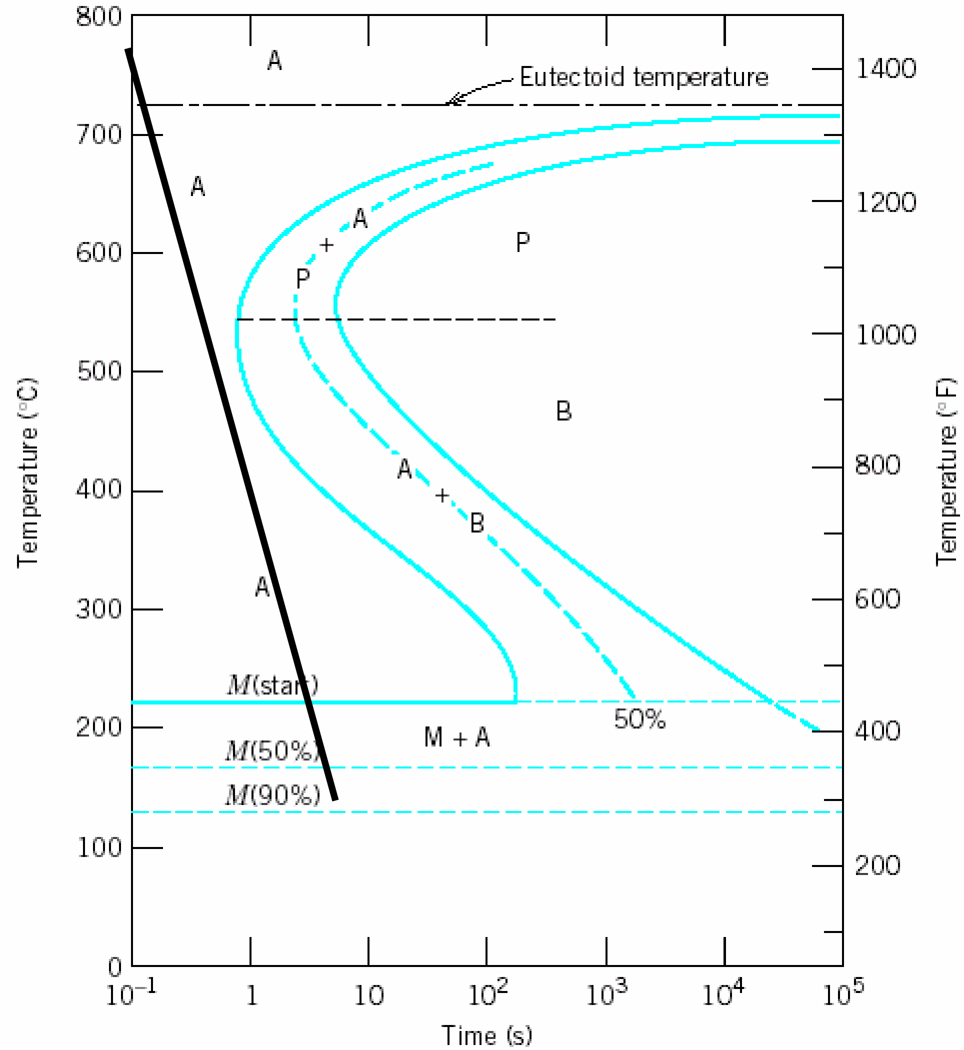


Martensite appearnace

Martentite needles

Retained austenite

Austenite that did not transform during quenching



Quenching rate has to be high enough to avoid hitting the nose of the curve

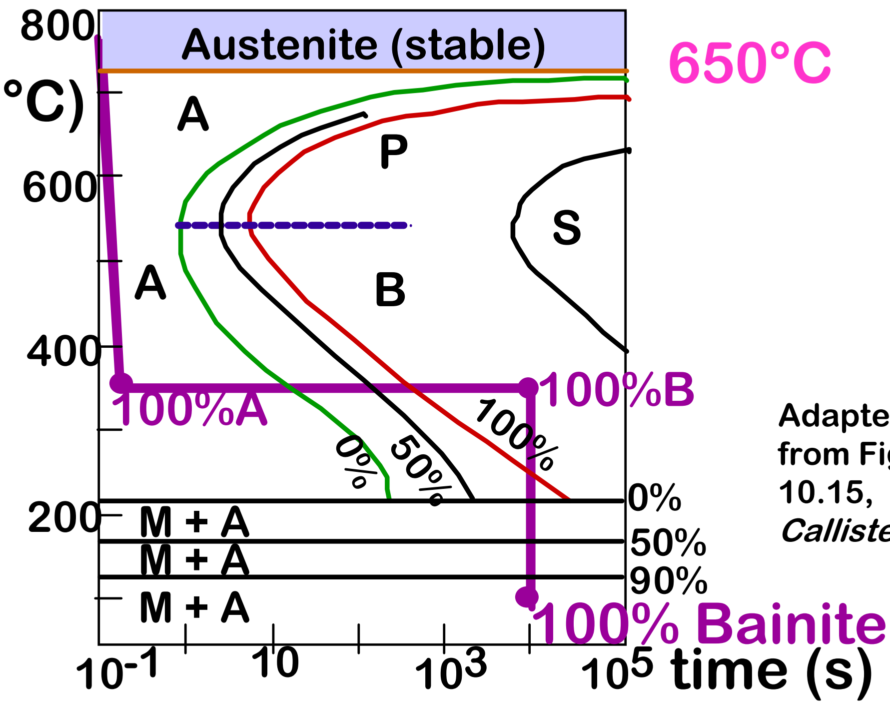
COOLING EX: Fe-C SYSTEM (1)

- $C_o = C_{eutectoid}$
- Three histories...

Rapid cool to:	Hold for:	Rapid cool to:	Hold for:	Rapid cool to:	
350°C	10^4s	T_{room}			(a)
250°C	10^2s	T_{room}			(b)
650°C	20s	400°C	10^3s	T_{room}	(c)

Case I

(a)



Adapted from Fig. 10.15, *Callister 6e.*

COOLING EX: Fe-C SYSTEM (2)

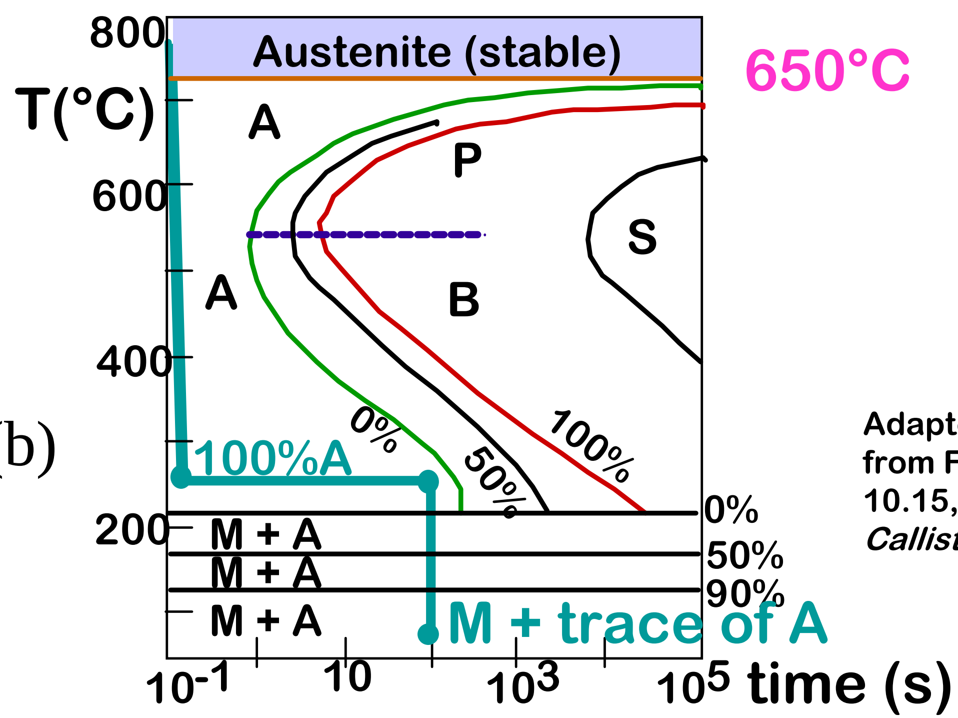
- $C_o = C_{eutectoid}$
- Three histories...

Rapid cool to:	Hold for:	Rapid cool to:	Hold for:	Rapid cool to:
350°C	10^4s	T_{room}		
250°C	10^2s	T_{room}		
650°C	20s	400°C	10^3s	T_{room}

(b)

Case II

(b)



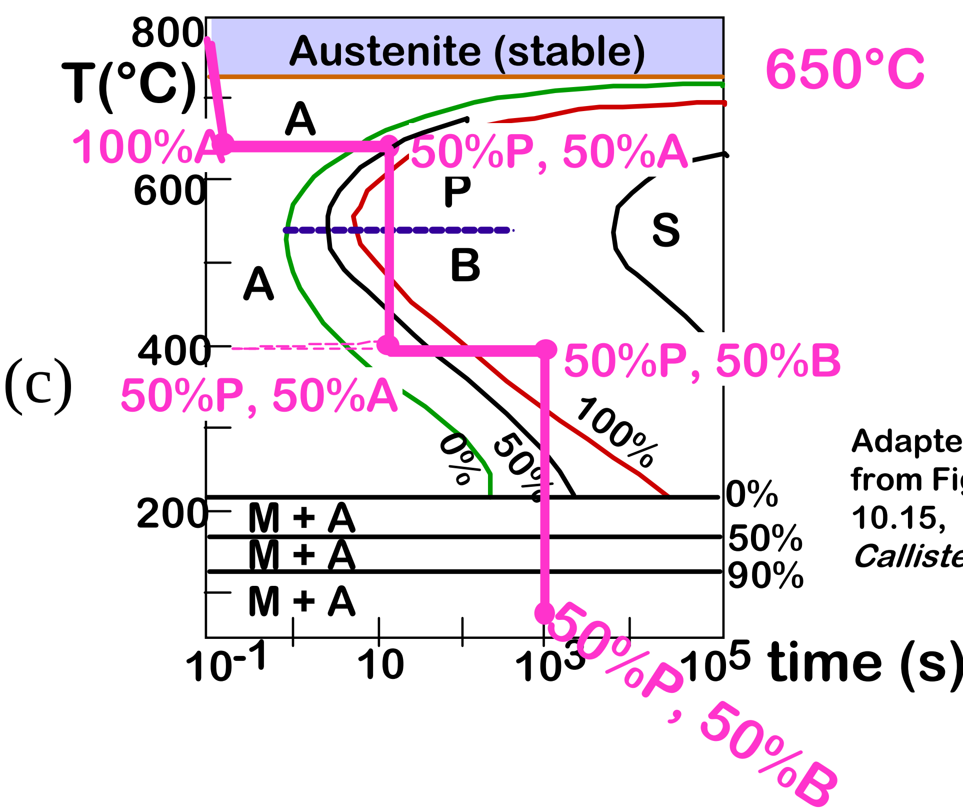
Adapted from Fig. 10.15, *Callister 6e.*

COOLING EX: Fe-C SYSTEM (3)

- $C_o = C_{eutectoid}$
- Three histories...

Rapid cool to:	Hold for:	Rapid cool to:	Hold for:	Rapid cool to:
350°C	10^4s	T_{room}		
250°C	10^2s	T_{room}		
650°C	20s	400°C	10^3s	T_{room} (c)

Case III



Adapted from Fig. 10.15, *Callister 6e*.

MECHANICAL PROPERTIES

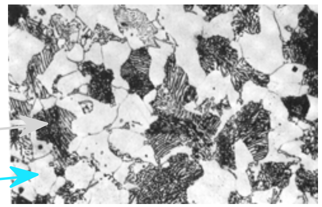
Pearlite: consist of alternating layers of soft α and hard fe_3c. Fine pearlite is stonger than coarse pearlite because there is greater phase boundary area per unit volume and these boundaries serve as barriers to dislocation motion. Coarse pearlite, on the other hand is more ductile than fine pearlite.

Spheroidite: The fe_3c phase which is considered as the reinforcing phase is coarse and this leads to less phase boundary area. Of all steel alloys, ones containing spheroidite are the softest and the weakest.

Bainite: Bainitic steels have fine structures (smaller ferrite and cementite phases) they are generally stronger and harder than pearlitic steels.

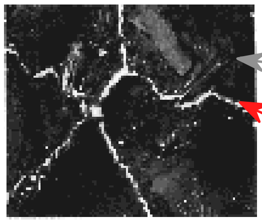
MECHANICAL PROPERTIES

- Effect of wt%C



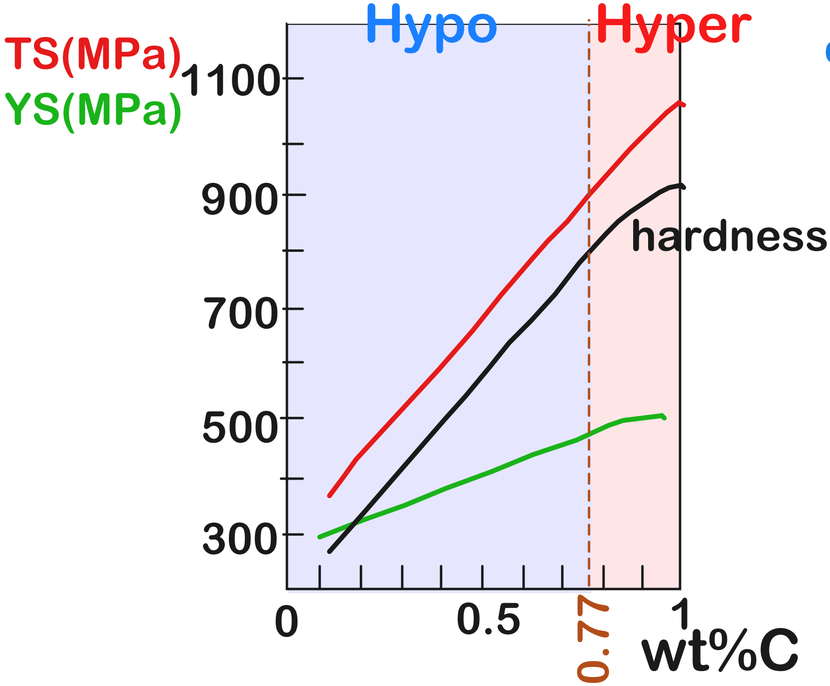
C_o<0.77wt%C

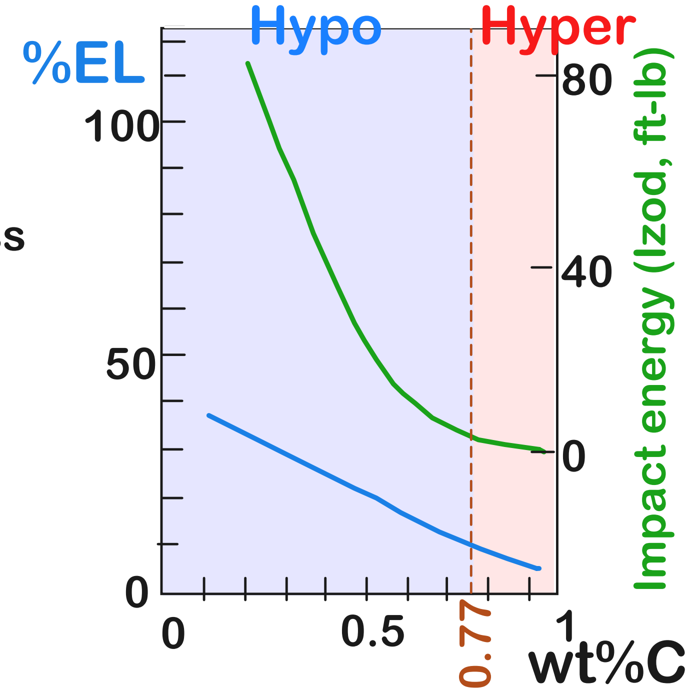
Hypoeutectoid



C_o>0.77wt%C

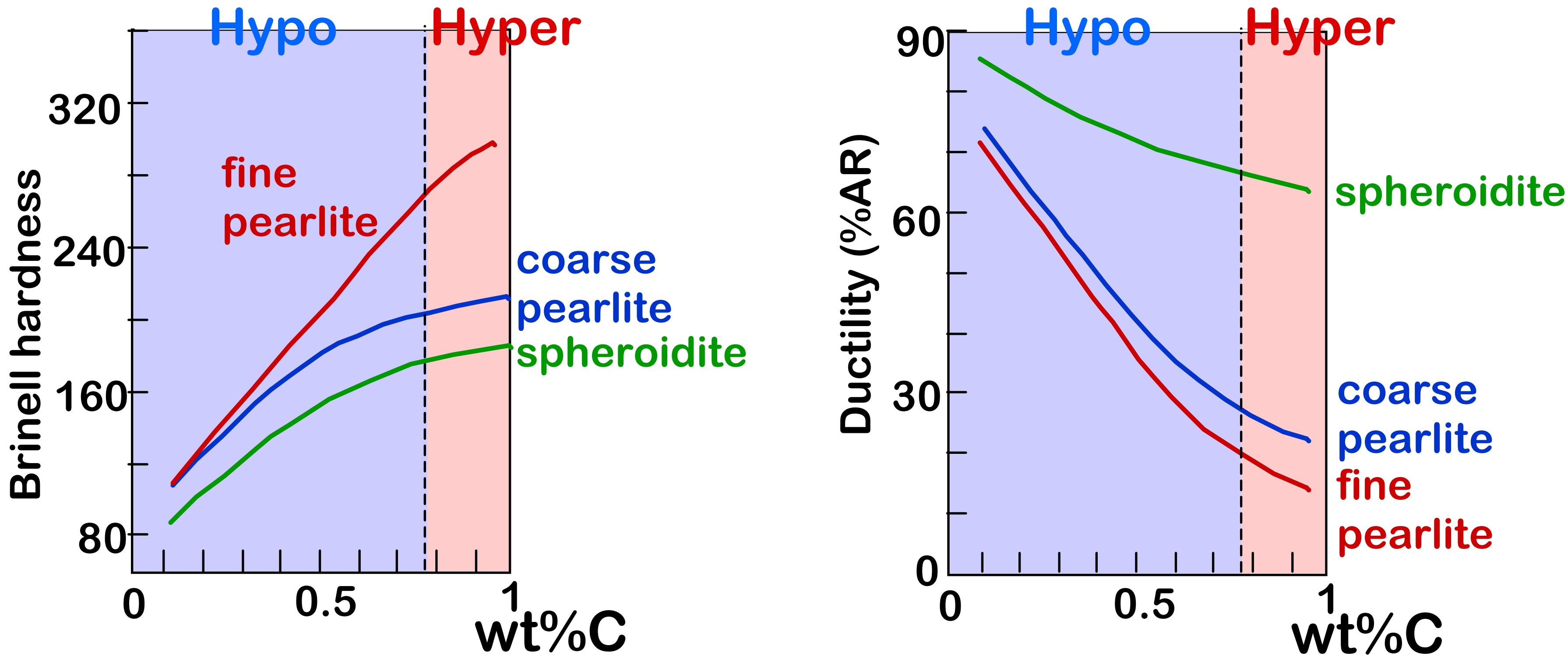
Hypereutectoid





- More wt%C: TS and YS increase, %EL decreases.

- Fine vs coarse pearlite vs spheroidite



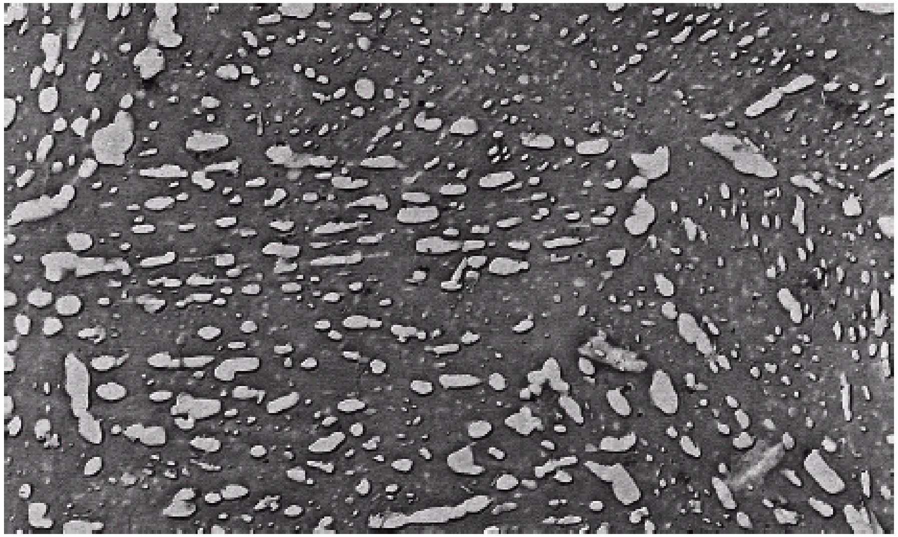
- Hardness: fine > coarse > spheroidite
- %AR: fine < coarse < spheroidite

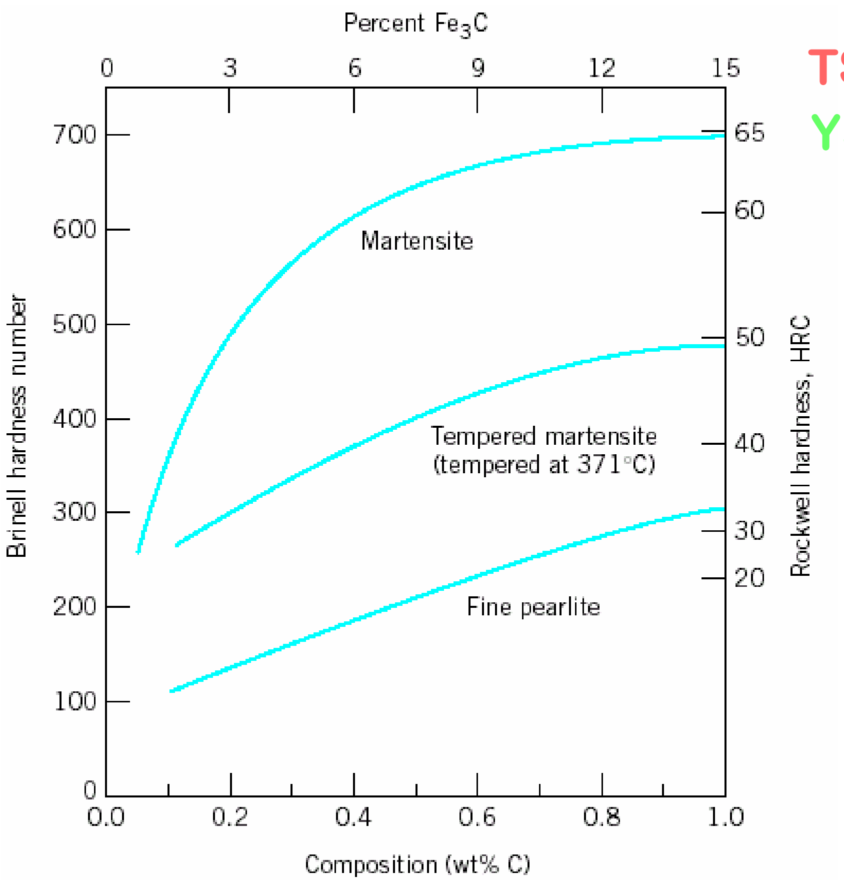
Martensite: The hardest and the strongest and in addition the most brittle.Its hardness is dependent on the carbon content upto about 0.6 wt% C. This strength is attributed to the effectiveness of interstitial trapped carbon atoms in hindering dislocation motion.

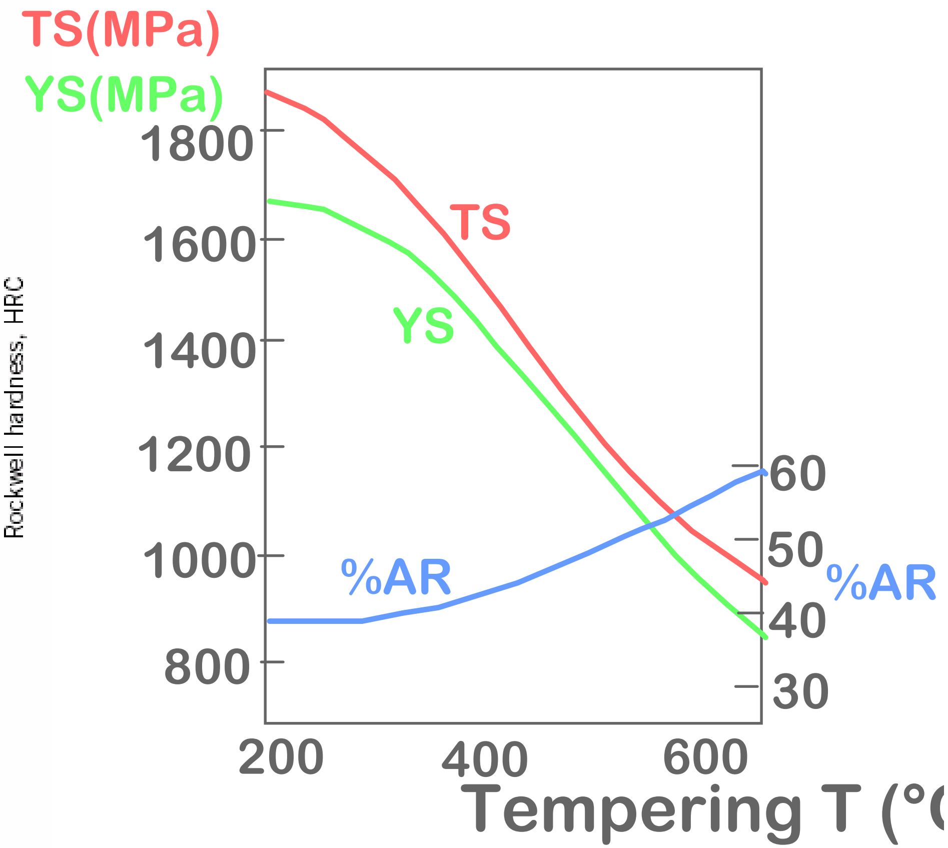
Tempered martensite:Ductility and toughness of martensite may be enhanced by a heat treatment called tempering, in which martensitic steels are heated to temperature in the range 250C to 650C.

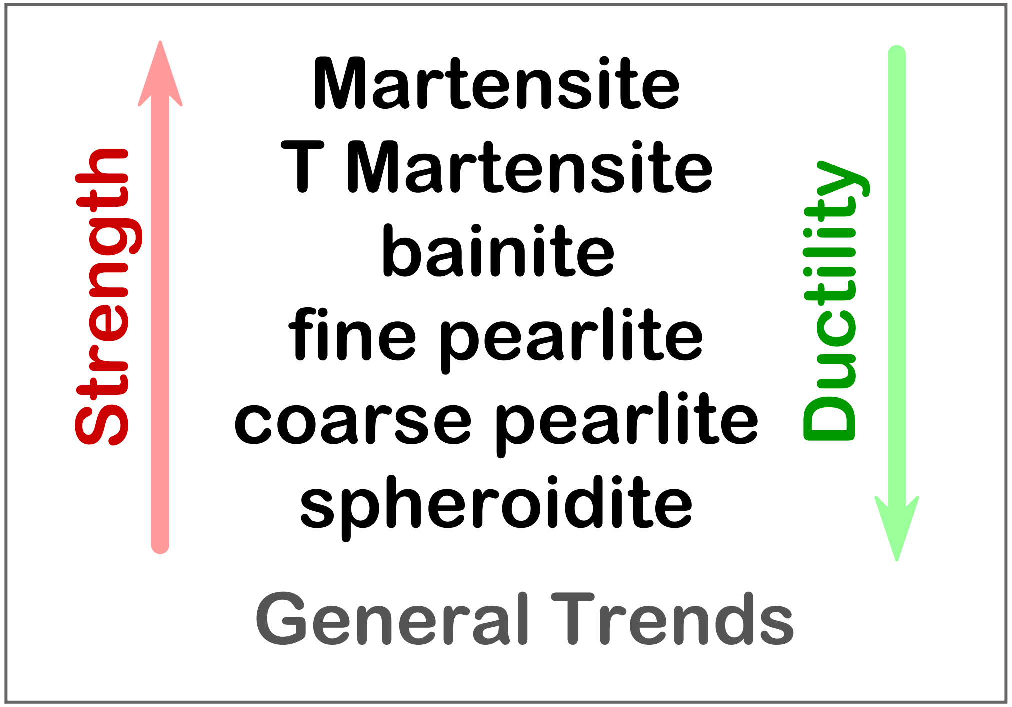
Martensite (BCT, single phase) → Tempered martensite (α + fe_3c phase)

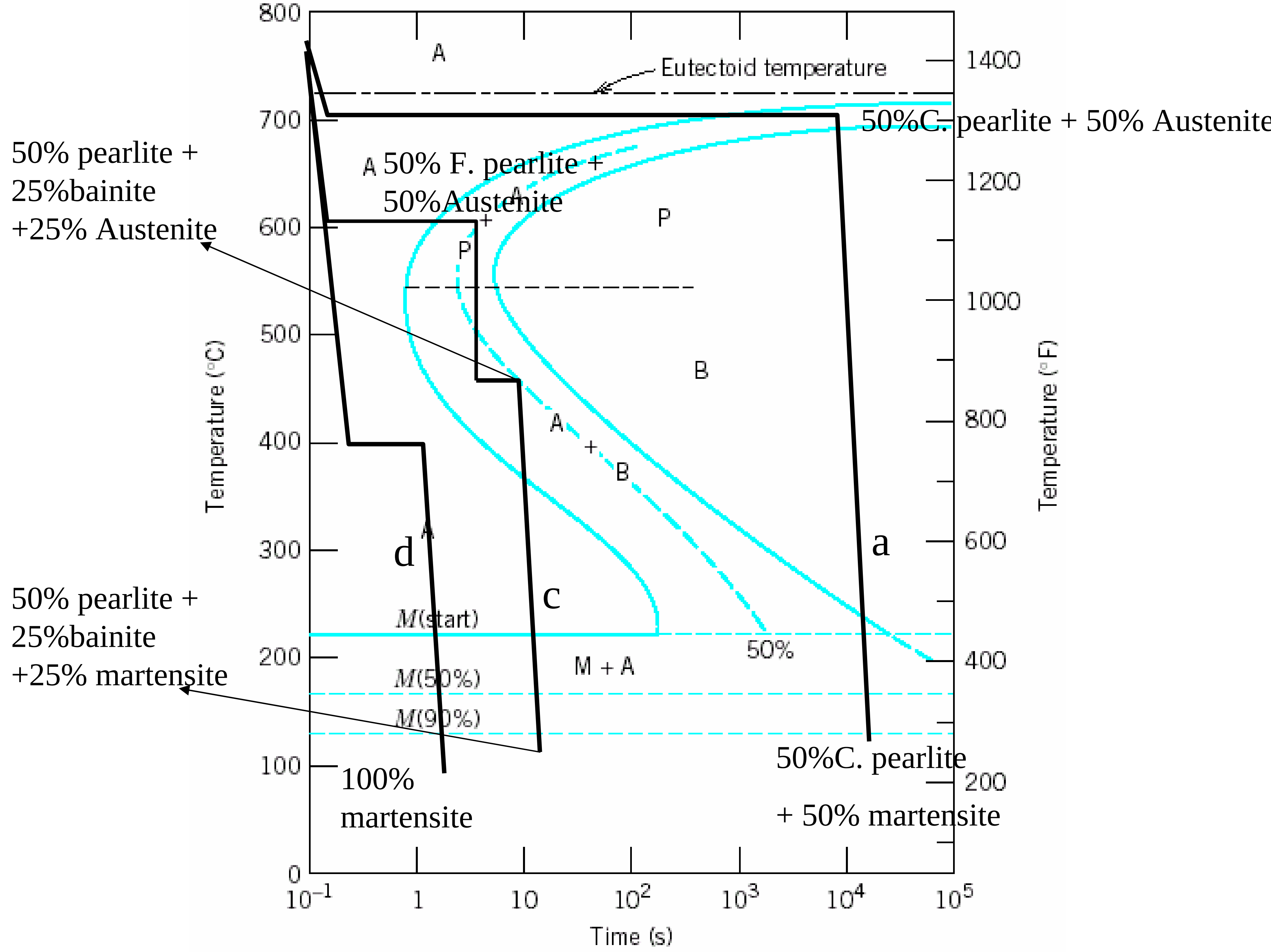
Extremely fine particles of fe_3c in α matrix



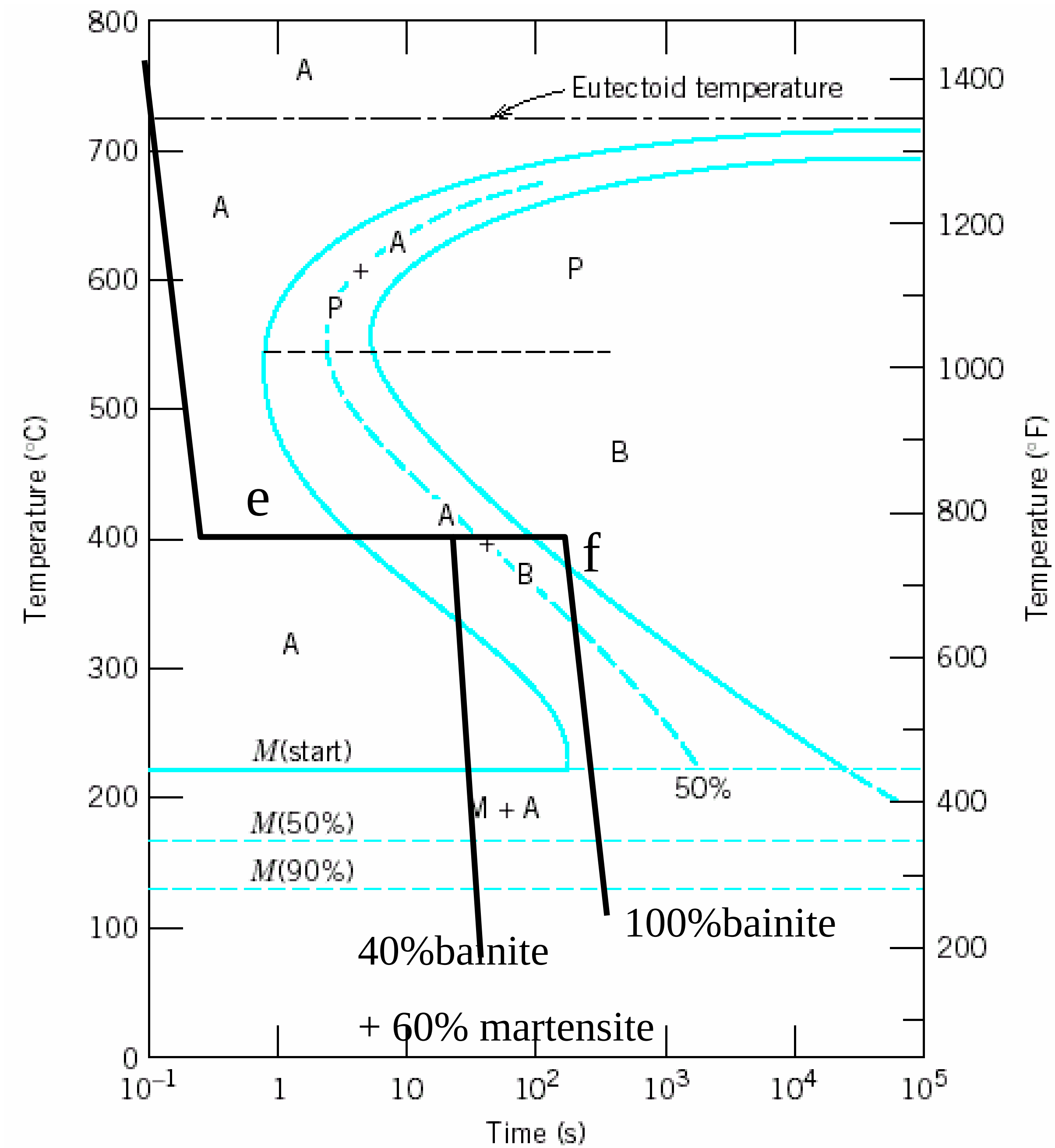

Percent Fe_3C
0
3
6
9
12
15
700
600
500
400
300
200
100
0
65
60
50
40
30
20
Martensite
Tempered martensite
(tempered at 371°C)
Fine pearlite
Brinell hardness number
Rockwell hardness, HRC
0.0
0.2
0.4
0.6
0.8
1.0
Composition (wt% C)


TS(MPa)
YS(MPa)
1800
1600
1400
1200
1000
800
TS
YS
%AR
60
50
40
30
%AR
200
400
600
Tempering T (°C)


Strength
Martensite
T Martensite
bainite
fine pearlite
coarse pearlite
spheroidite
Ductility
General Trends



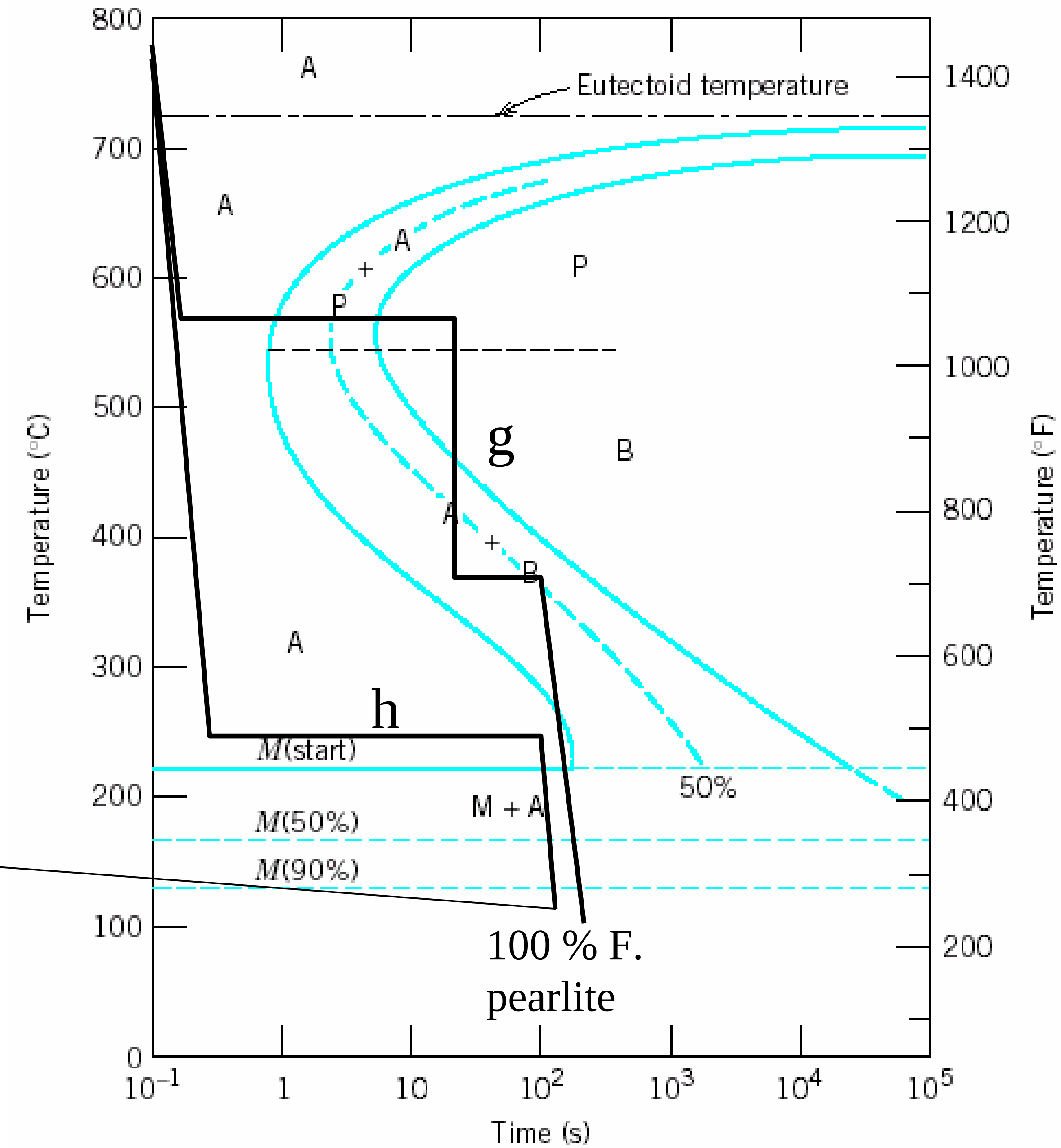
50% pearlite +
25%bainite
+25% Austenite
50% pearlite +
25%bainite
+25% martensite
A
Eutectoid temperature
50%C. pearlite + 50% Austenite
A 50% F. pearlite +
50%Austenite
P
P
B
A
+
B
d
c
a
M(start)
M + A
50%
M(50%)
M(90%)
100%
martensite
50%C. pearlite
+ 50% martensite
Temperature (°C)
Temperature (°F)
Time (s)
800
700
600
500
400
300
200
100
0
1400
1200
1000
800
600
400
200
10^{-1}
1
10
10^2
10^3
10^4
10^5



800
700
600
500
400
300
200
100
0
Temperature (°C)
1400
1200
1000
800
600
400
200
Temperature (°F)
A
Eutectoid temperature
A
A
+
P
P
B
e
A
+
B
f
A
M(start)
M + A
50%
M(50%)
M(90%)
100%bainite
40%bainite
+ 60% martensite
10^{-1}
1
10
10^2
10^3
10^4
10^5
Time (s)

100% martensite

When reheated at 315C for 1 hour we get tempered martensite



(a) 50% coarse pearlite and 50% martensite

(b) 100% spheroidite

(c) 50% fine pearlite, 25% bainite , and 25% martensite

(d) 100% martensite

(e) 40% bainite and 60% martensite

(f) 100% bainite

(g) 100% fine pearlite

(h) 100% tempered martensite