



Phase Diagrams

Vikash Kumar

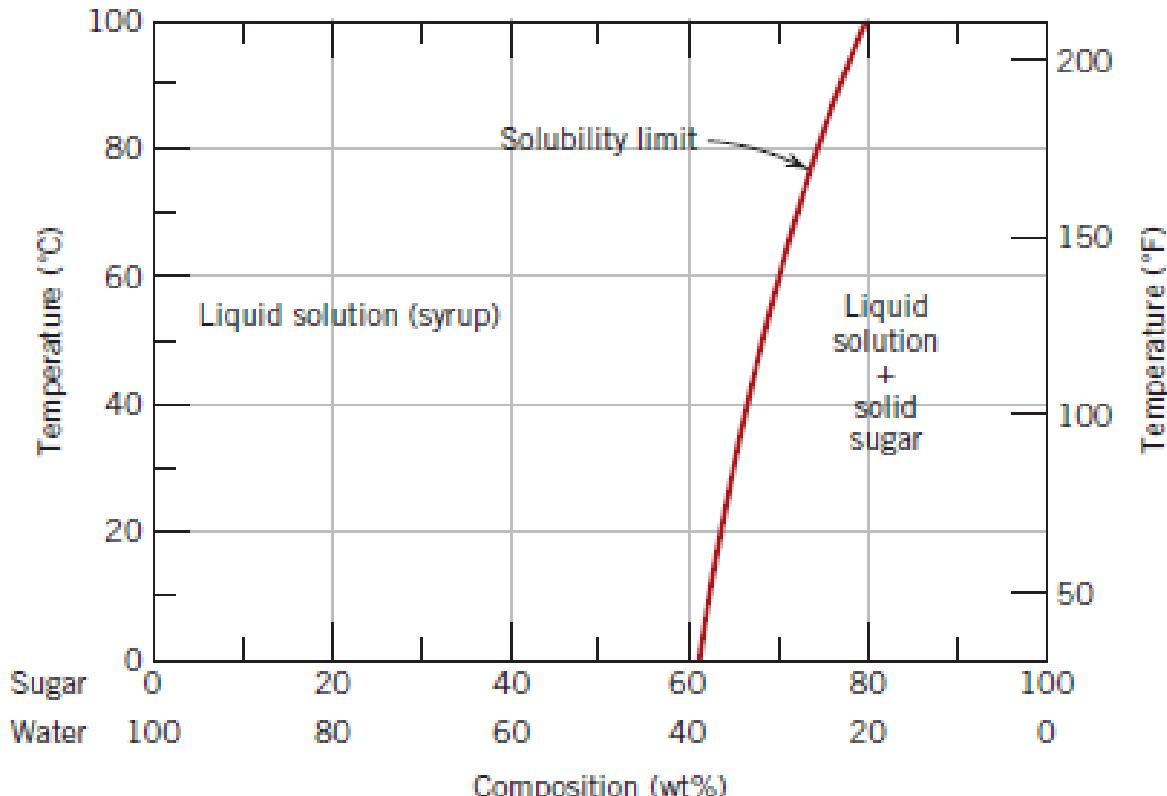
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Solubility Limit

Solubility limit: For many alloy systems and at some specific temperature, there is a maximum concentration of solute atoms that may dissolve in the solvent to form a solid solution

- Water continues to dissolve sugar till a certain limit called *solubility limit*.
- Beyond this limit, sugar does not dissolve and thus, remain as a separate substance within the sugar–water solution.
- Solubility is temperature dependent.

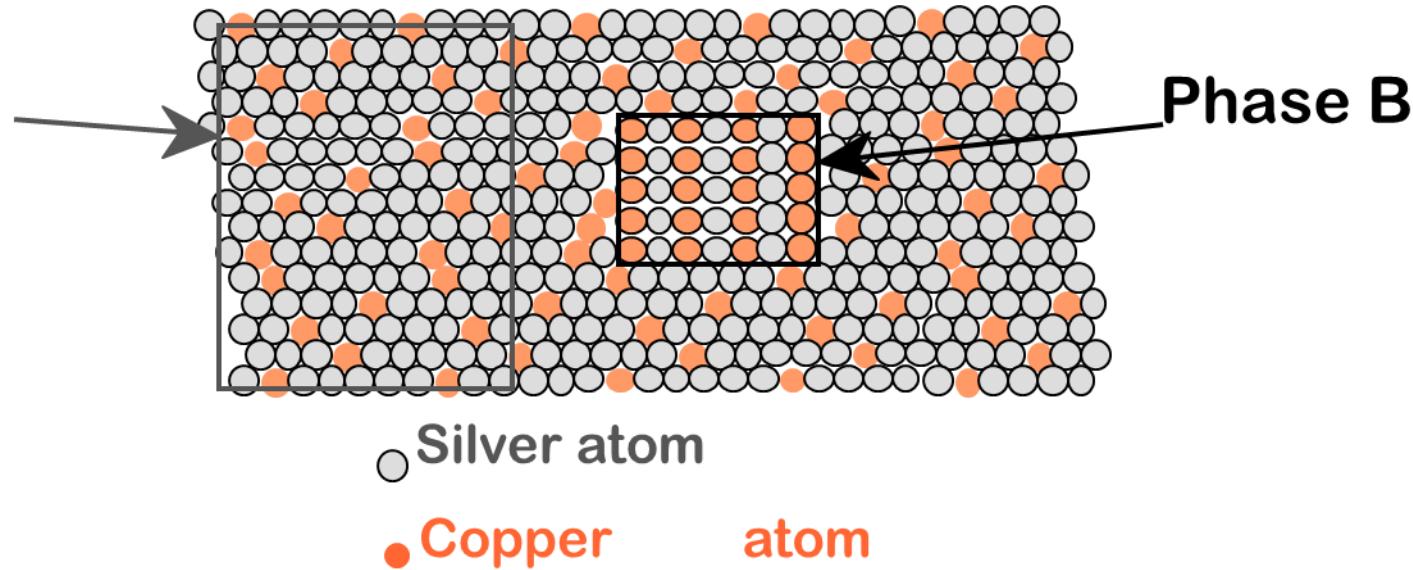


The solubility of sugar ($C_{12}H_{22}O_{11}$) in a sugar–water syrup.

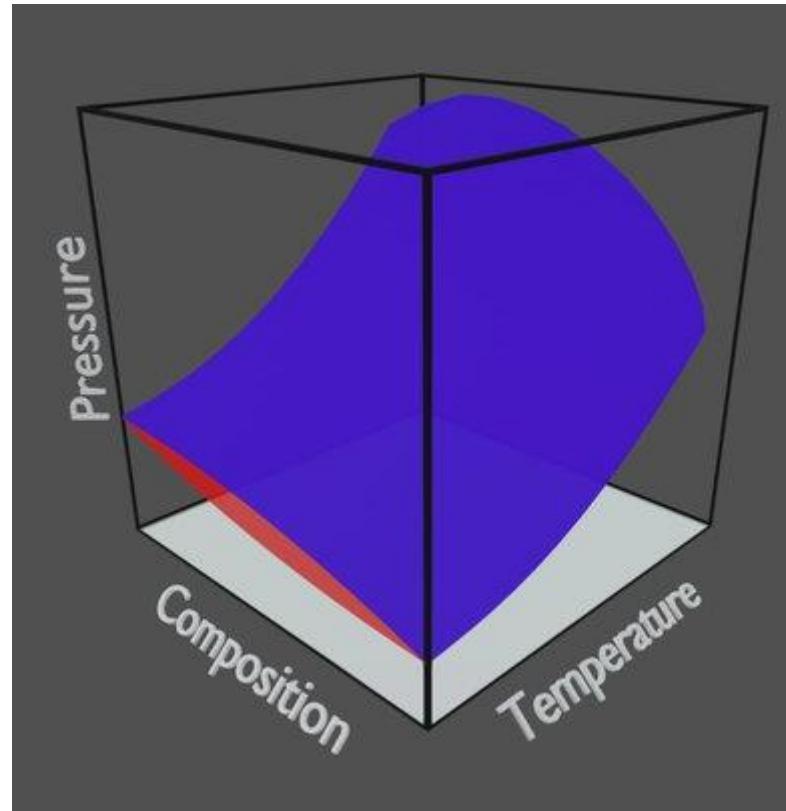
Definition of a phase

- Homogeneous portion of a system that has uniform physical and chemical characteristics.
- When two phases exist in a system, they can differ in either physical properties or in chemical properties or in both.
- Examples: Sugar–Water solution (Phase A) + Solid sugar (Phase B);
Ice(Phase A) + Water(Phase B)
- Existence of a solid substance in two or more polymorphic forms, like FCC, BCC is possible.
Then, each of these structures within the substance is a phase.

Phase A

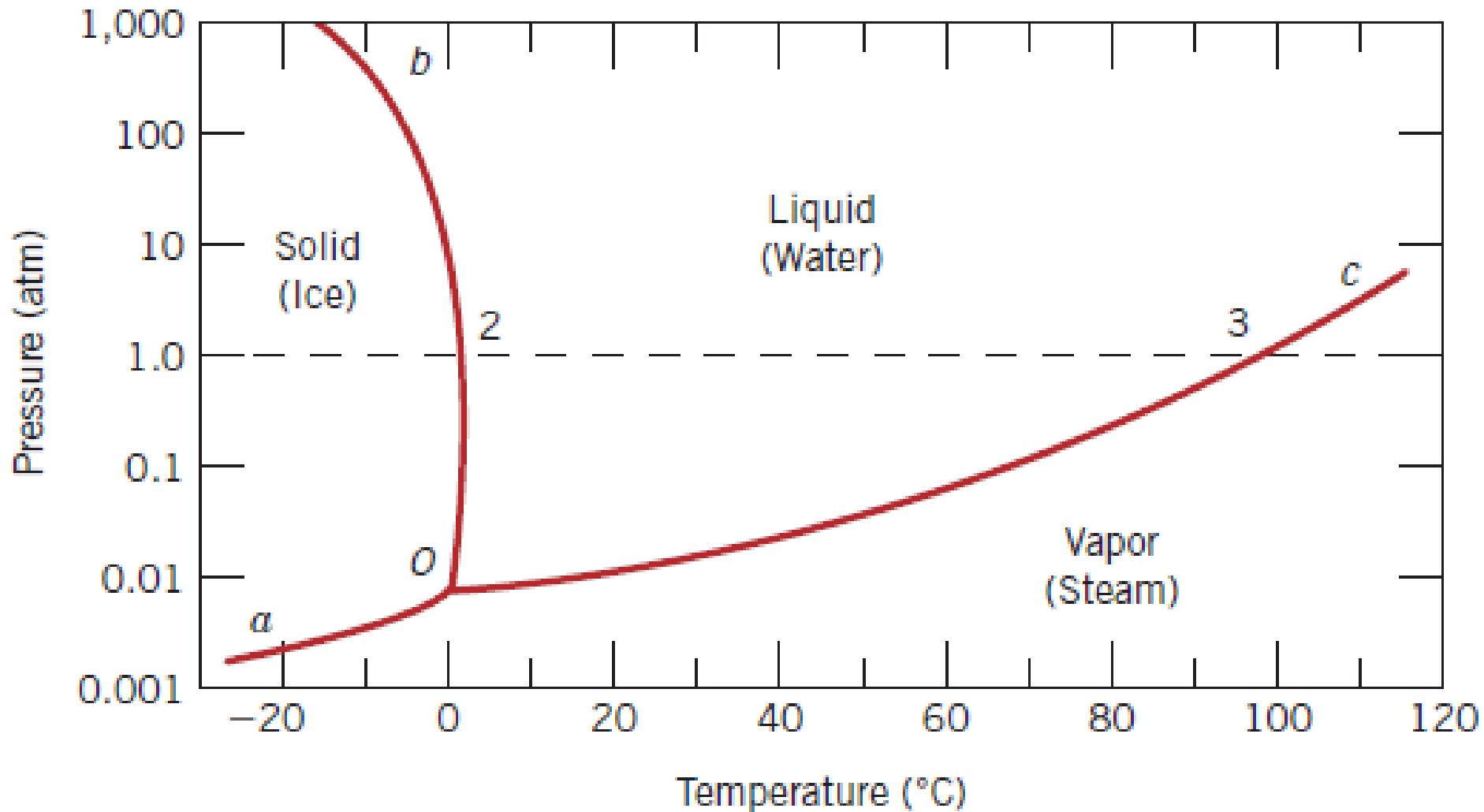


Control of the phase structure of a particular system by three externally controllable parameters (temperature, pressure, and composition) described concisely by **Phase diagram**.



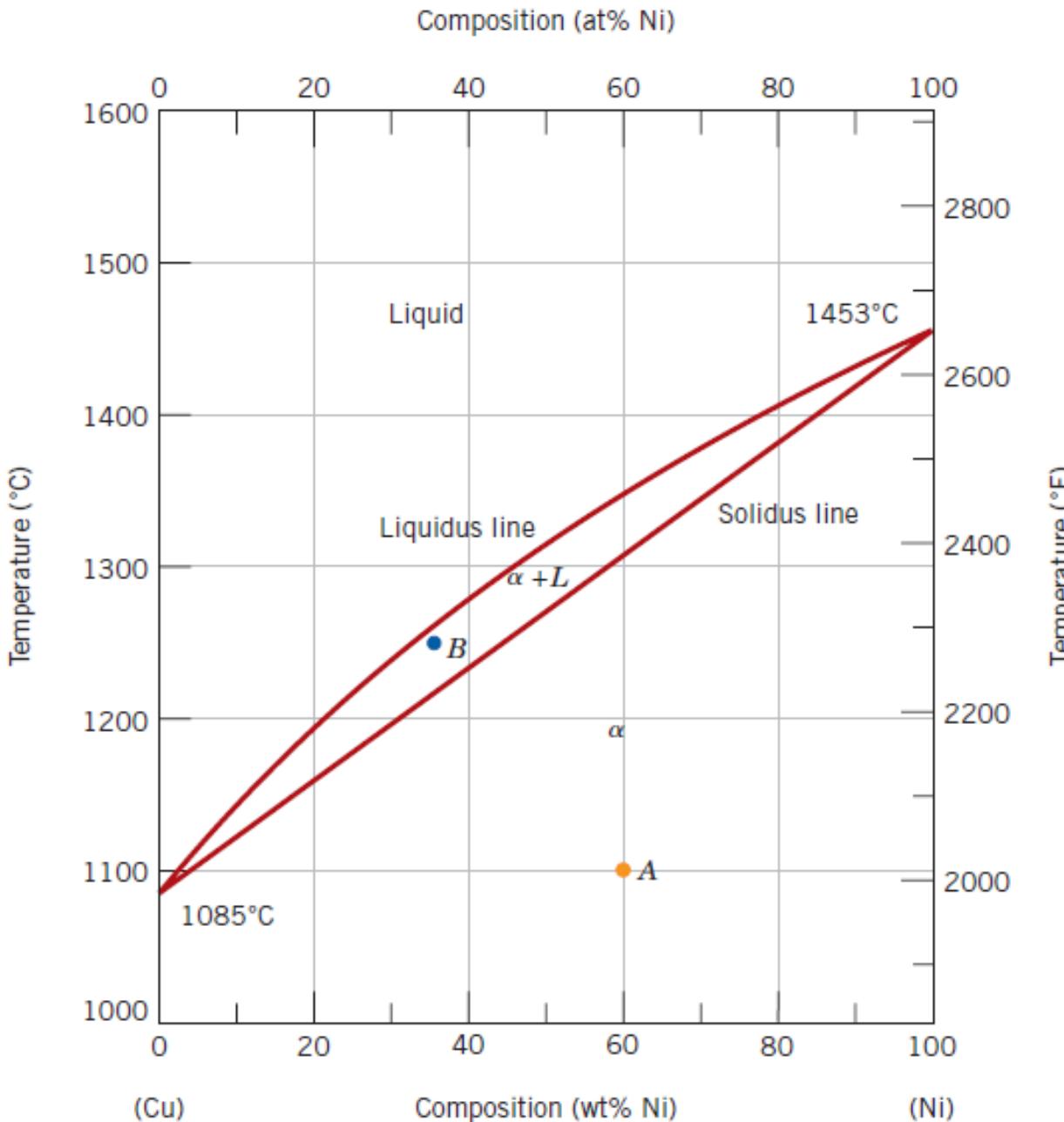
One Component/Unary Phase Diagrams

- Phase diagram of a pure substance. Only pressure and temperature are the variables.
- Triple point.



Binary Phase Diagrams - an isomorphous system

- Cu – Ni System: an **isomorphous system** (no solubility limit).
- Complete solubility below 1080°C. They have same crystal structure (FCC), nearly identical atomic radii and electronegativities and similar valences – which are all requirements for substitutional type of defects.
- Metallic solid solutions are commonly designated by lowercase Greek letters α , β , γ etc.
- The phase boundary separating $(\alpha + L)$ and L is called **liquidus**. The one separating $(\alpha + L)$ and α is called **Solidus**.
- The intersection points of the these boundaries are the respective melting points.
- Find Phase(s) at A? Phase(s) at B?



Binary Phase Diagrams – Interpretation

To find the composition of α and L phases

- A horizontal line in the phase diagram is an isotherm also called **Tie line**.
- Draw a tie line passing through the point B .
- The composition of L phase is given by C_L and that of α is given by C_α .

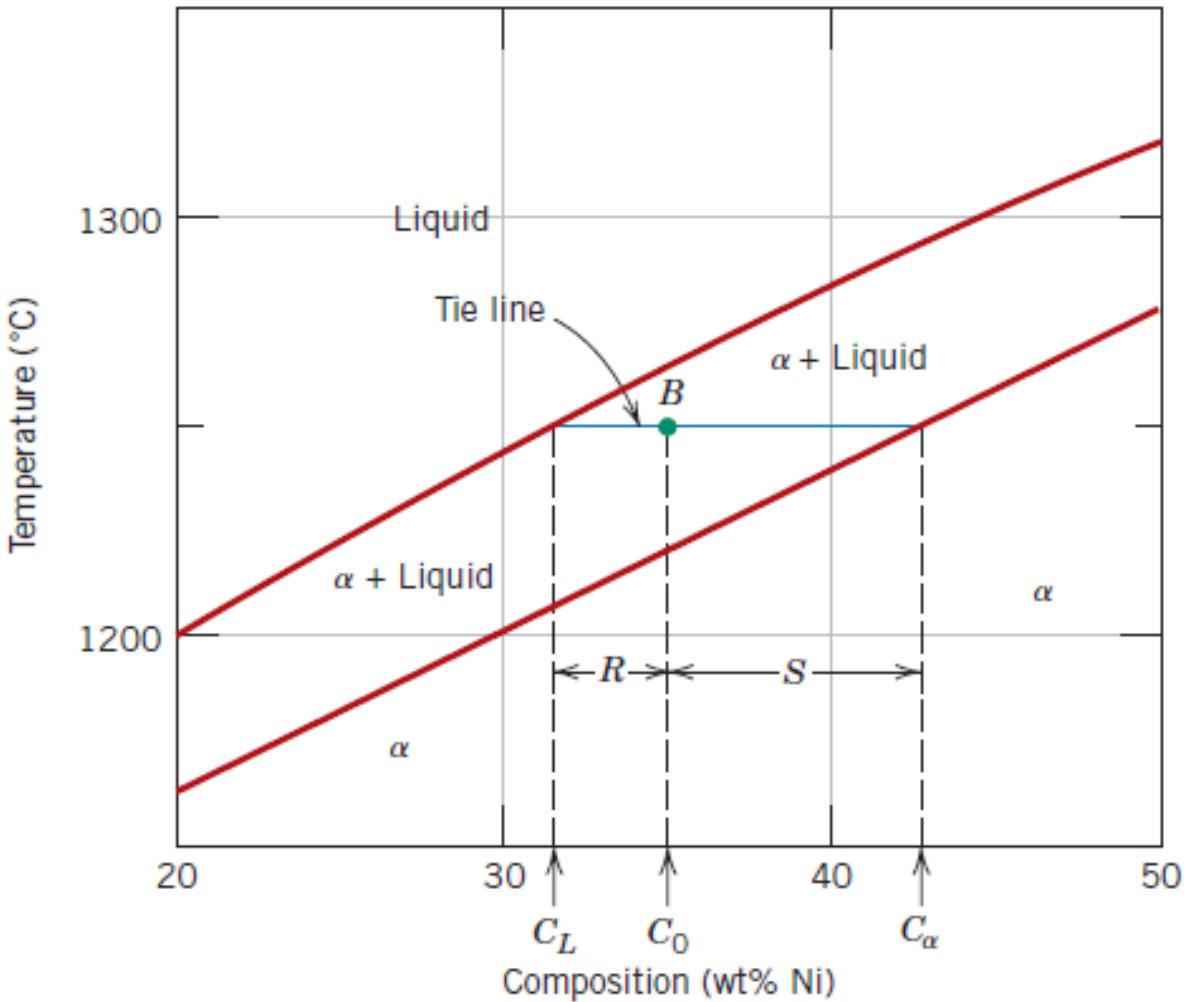
To find phase fractions – **Lever Rule**

$$W_L = \frac{S}{R + S}$$

$$= \frac{C_\alpha - C_0}{C_\alpha - C_L}$$

$$W_\alpha = \frac{R}{R + S}$$

$$= \frac{C_0 - C_L}{C_\alpha - C_L}$$

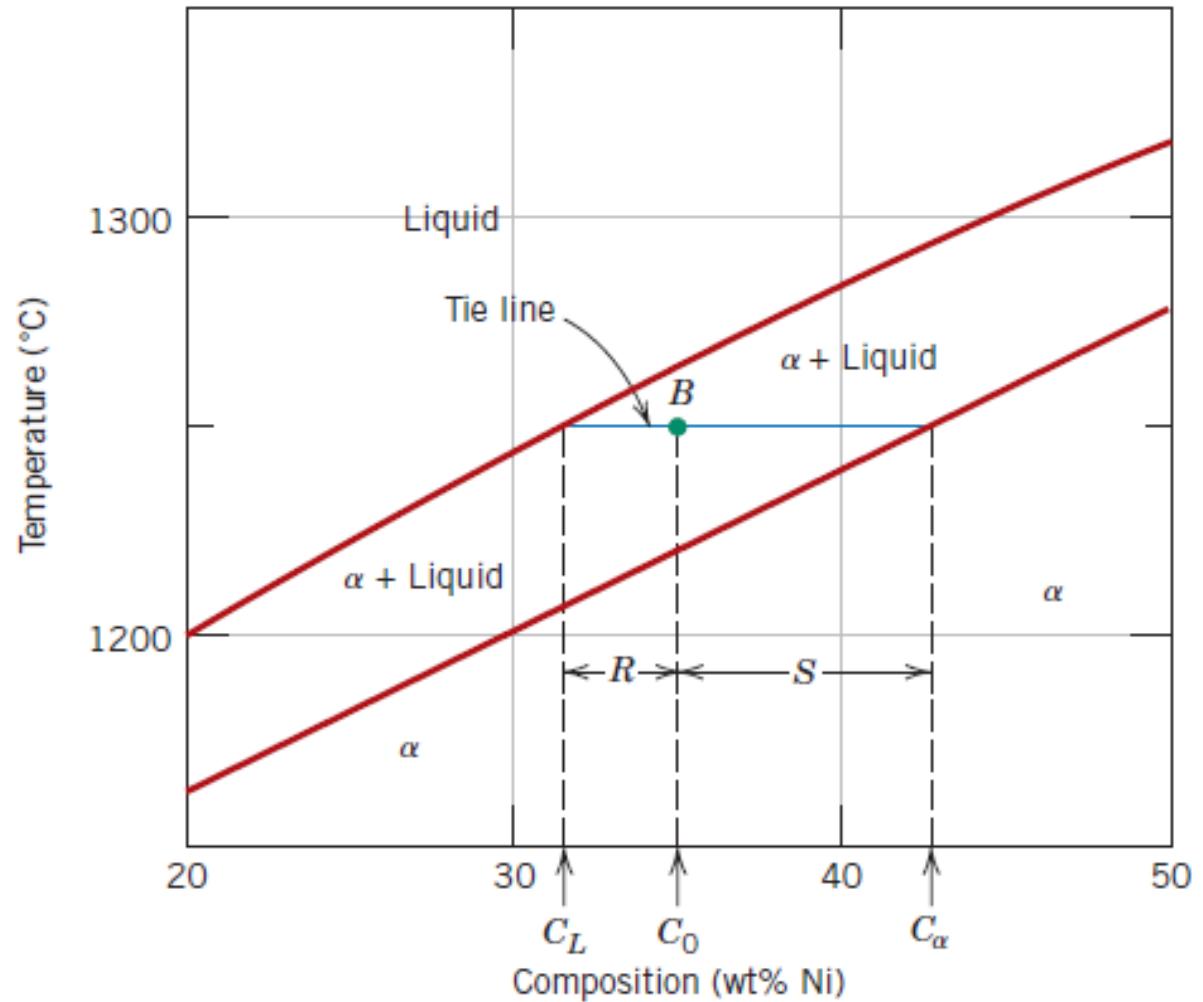


Binary Phase Diagrams – Interpretation

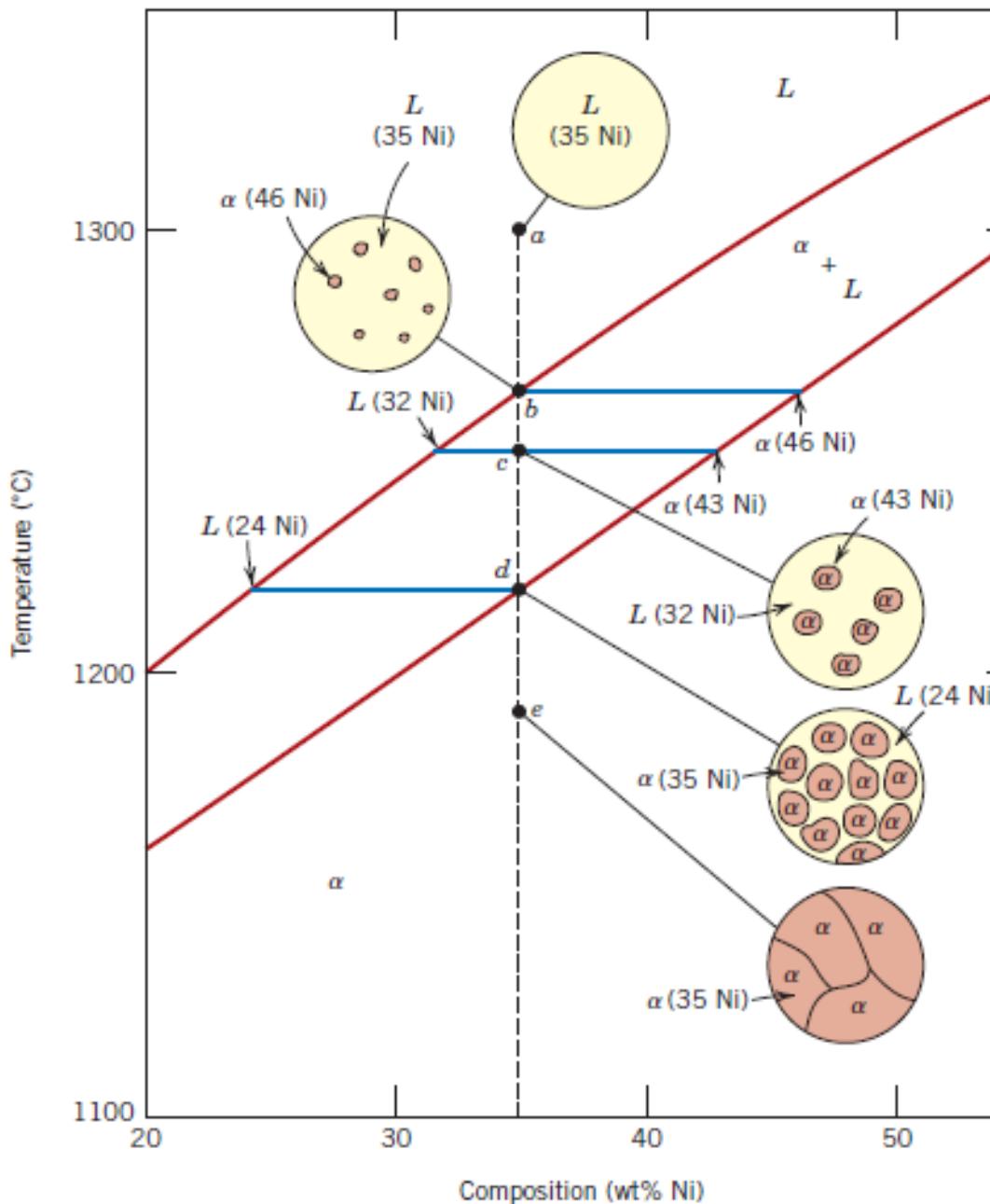
1) Phases Present?

2) Determination of Phase Compositions?

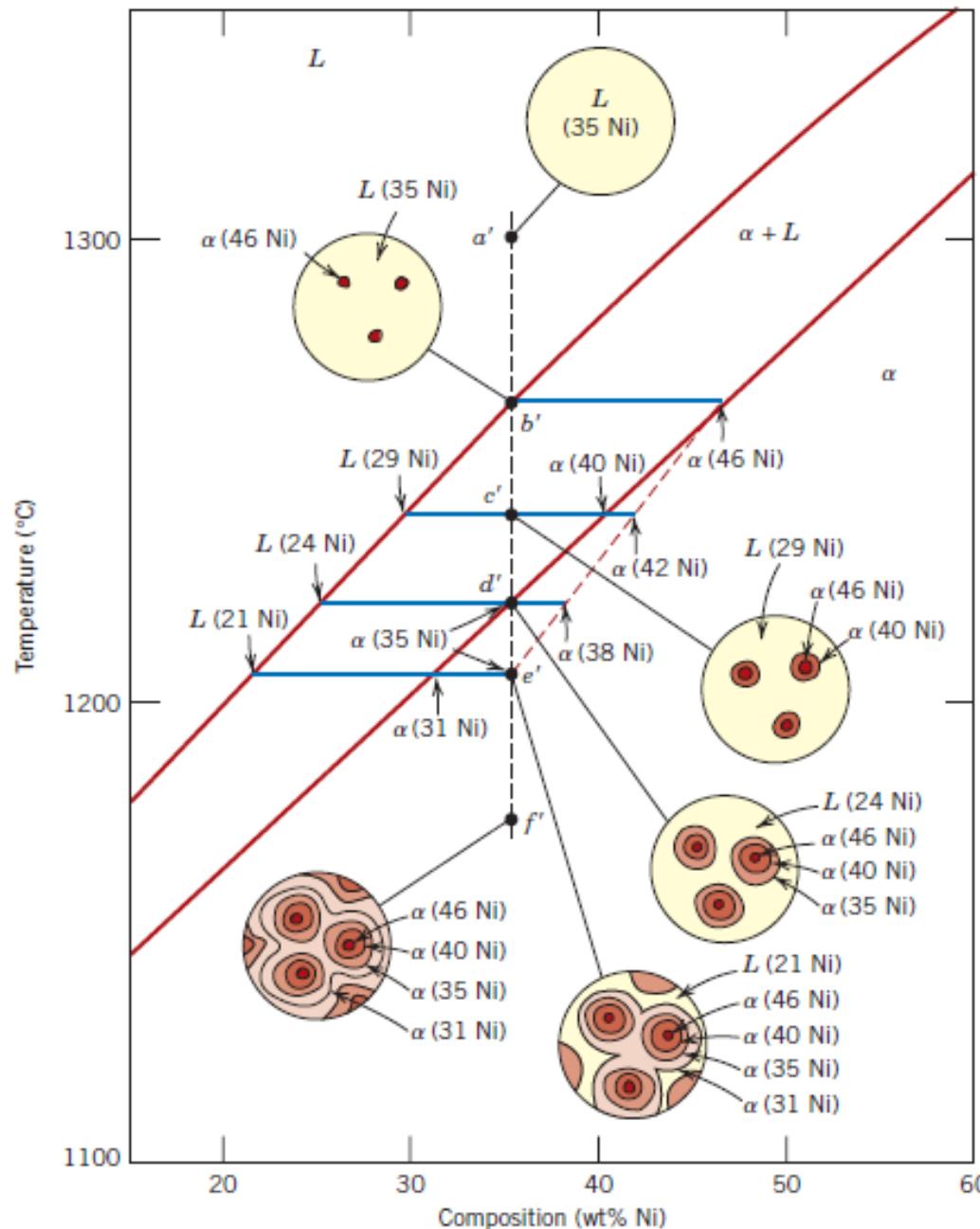
3) Determination of Phase Amounts?



Development of Microstructure – Equilibrium Cooling



Development of Microstructure – Nonequilibrium Cooling



Binary Phase Diagrams – Interpretation

- For multi-phase alloys (more than two), volume fractions are preferred.

$$V_\alpha = \frac{v_\alpha}{v_\alpha + v_\beta}$$

$$V_\alpha = \frac{\frac{W_\alpha}{\rho_\alpha}}{\frac{W_\alpha}{\rho_\alpha} + \frac{W_\beta}{\rho_\beta}}$$

$$V_\beta = \frac{\frac{W_\beta}{\rho_\beta}}{\frac{W_\alpha}{\rho_\alpha} + \frac{W_\beta}{\rho_\beta}}$$

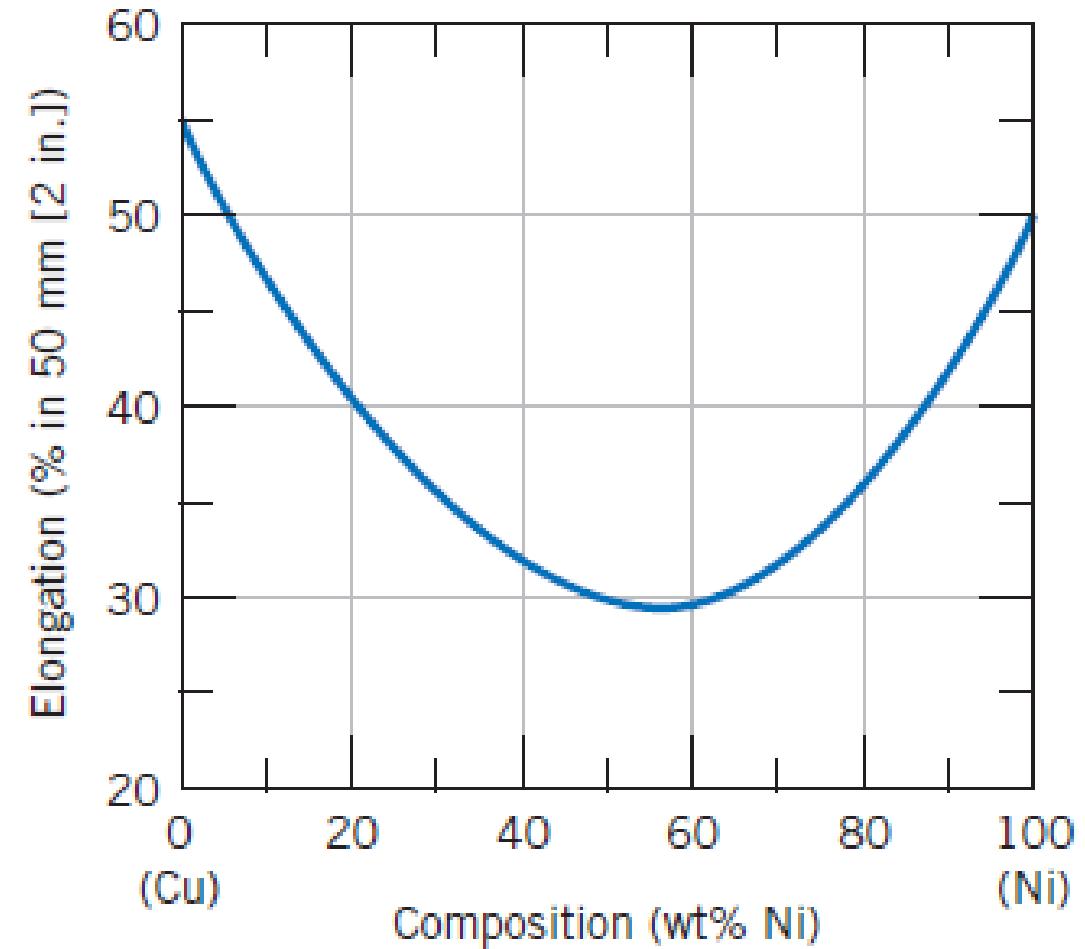
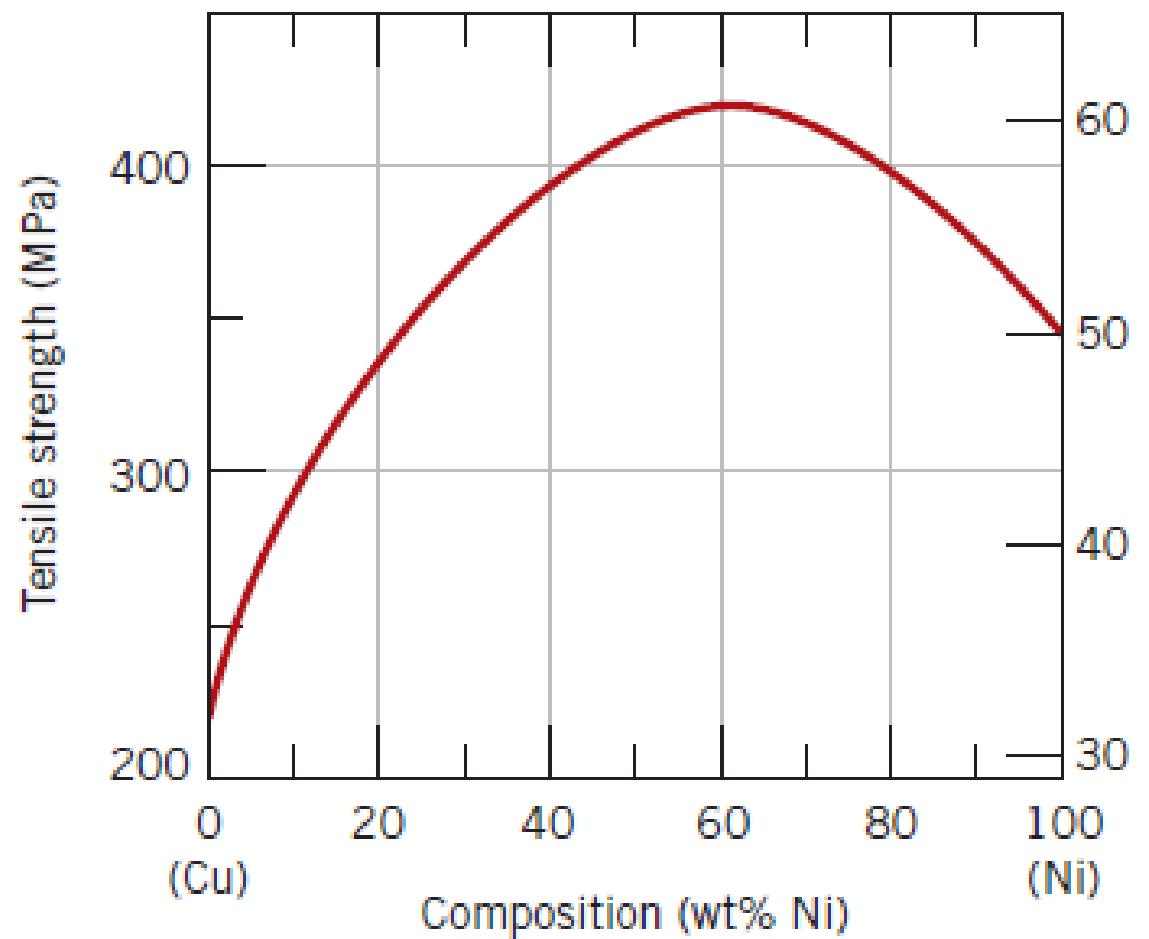
$$W_\alpha = \frac{V_\alpha \rho_\alpha}{V_\alpha \rho_\alpha + V_\beta \rho_\beta}$$

$$W_\beta = \frac{V_\beta \rho_\beta}{V_\alpha \rho_\alpha + V_\beta \rho_\beta}$$

To determine the density of a binary alloy, given the composition in terms of weight percent

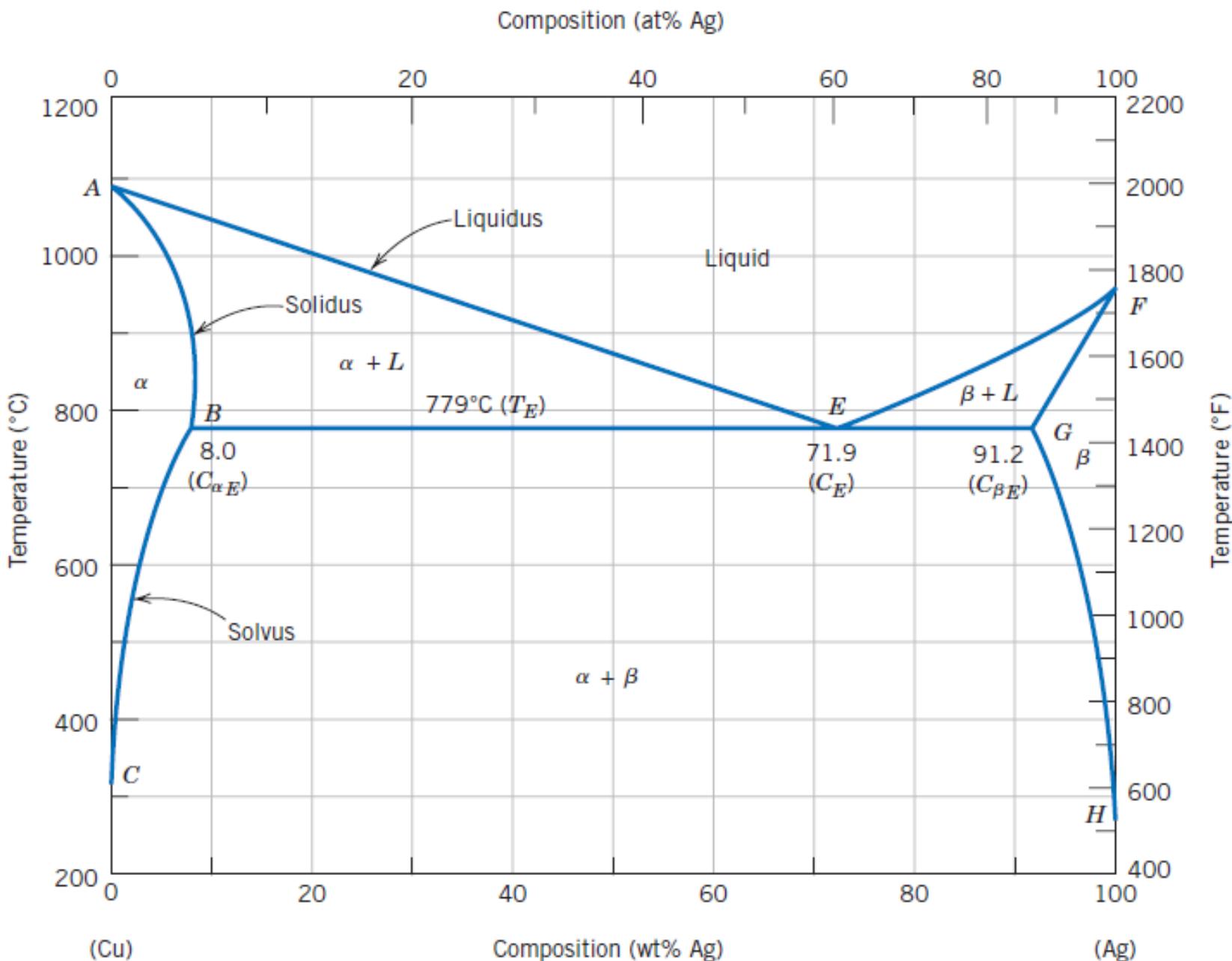
$$\rho_{\text{ave}} = \frac{100}{\frac{C_1}{\rho_1} + \frac{C_2}{\rho_2}}$$

Mechanical Properties of Isomorphous Alloys



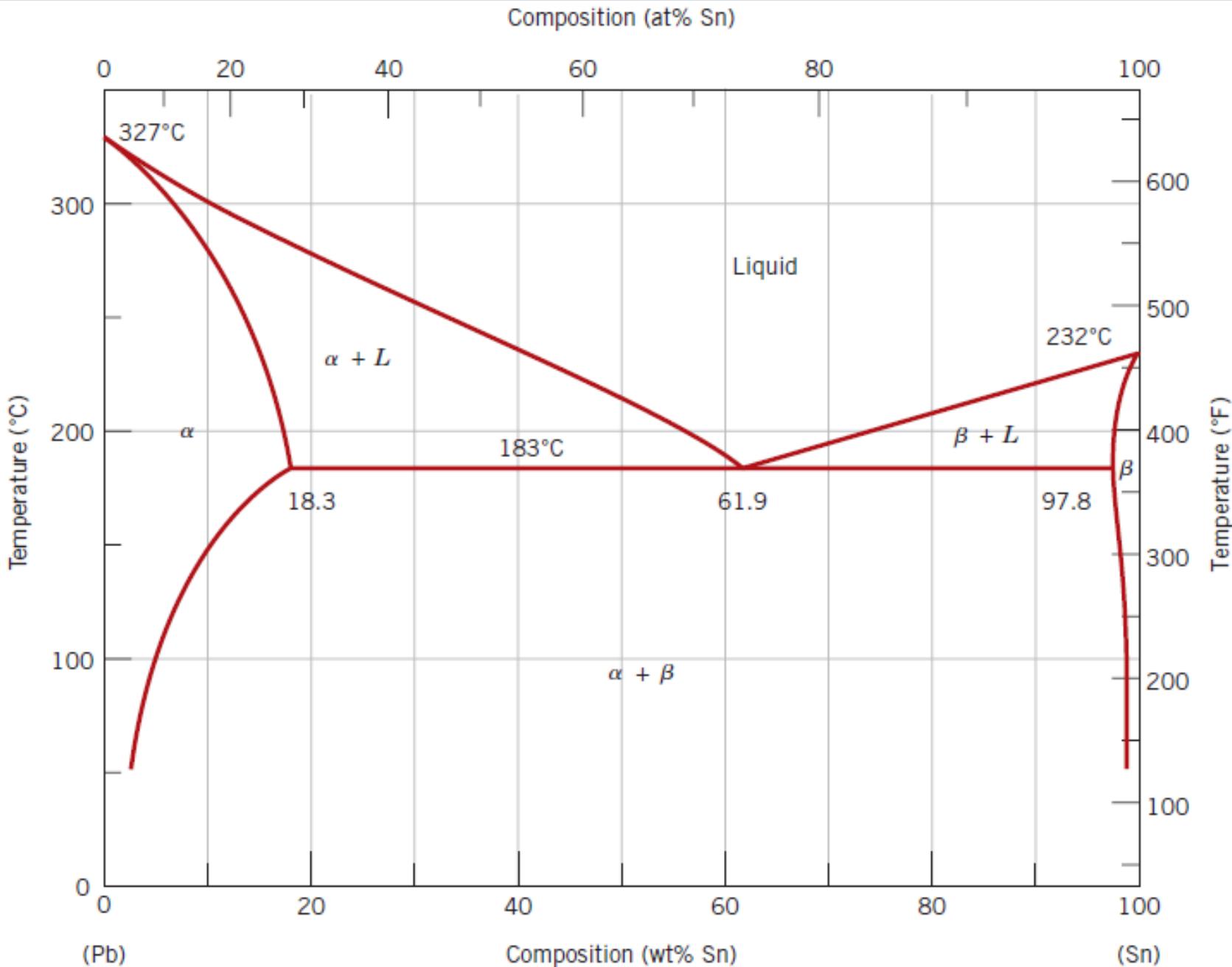
Binary Eutectic Systems – Cu + Ag

- Three single-phase regions are found on the diagram: α , β , and liquid.
- The α phase is a solid solution rich in copper; it has silver as the solute component and an FCC structure.
- The β -phase solid solution also has an FCC structure, but copper is the solute
 - Solubility limit
 - Solidus
 - Liquidus
 - Solvus
 - Melting temperature
 - Eutectic Reaction at E
 - Eutectic Isotherm (SolidusLine BEG)
 - Eutectic system



Binary Eutectic Systems – Pb + Sn

- Solubility limit
- Solidus
- Liquidus
- Solvus
- Melting temperature
- Eutectic Reaction
- Eutectic Isotherm
- Eutectic Composition



Lead-free solders – Sn + Bi

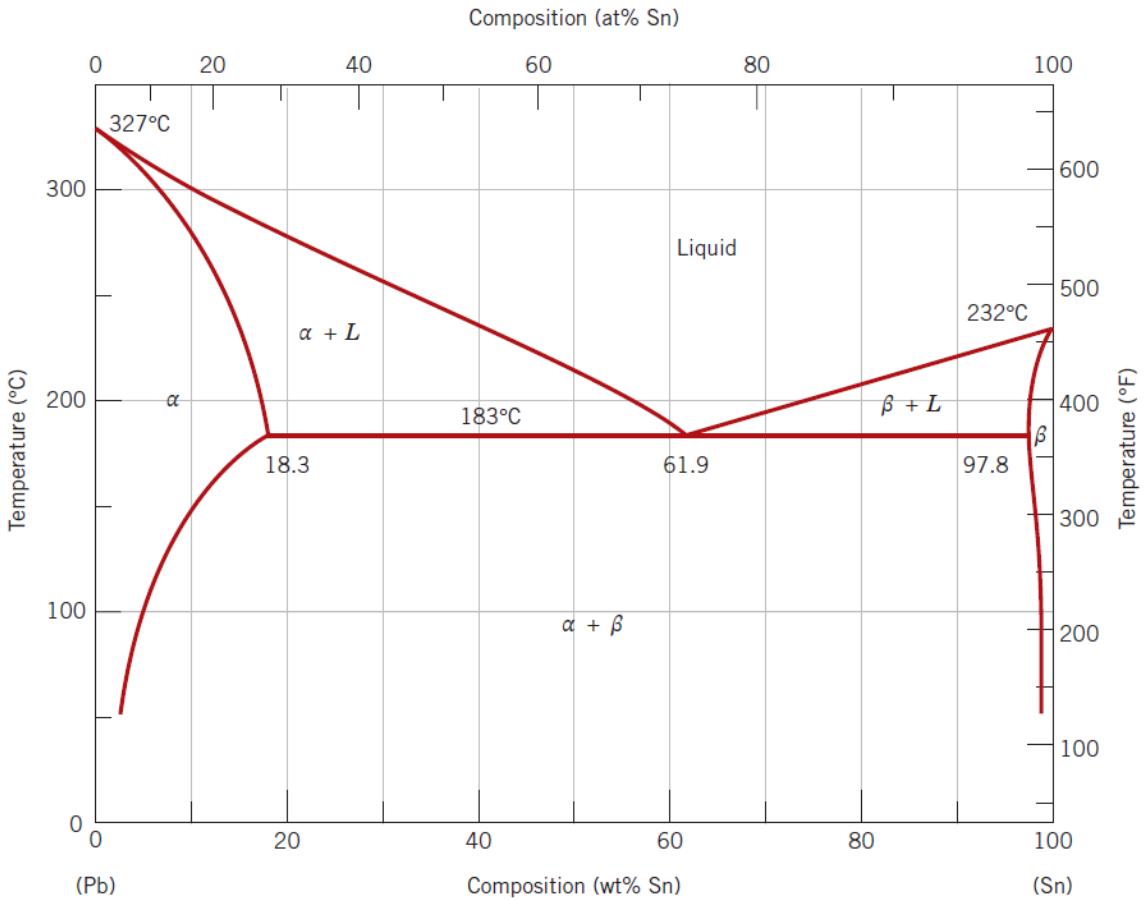
Ternary alloys as lead-free solders. Various alloy compositions for lead-free solders.

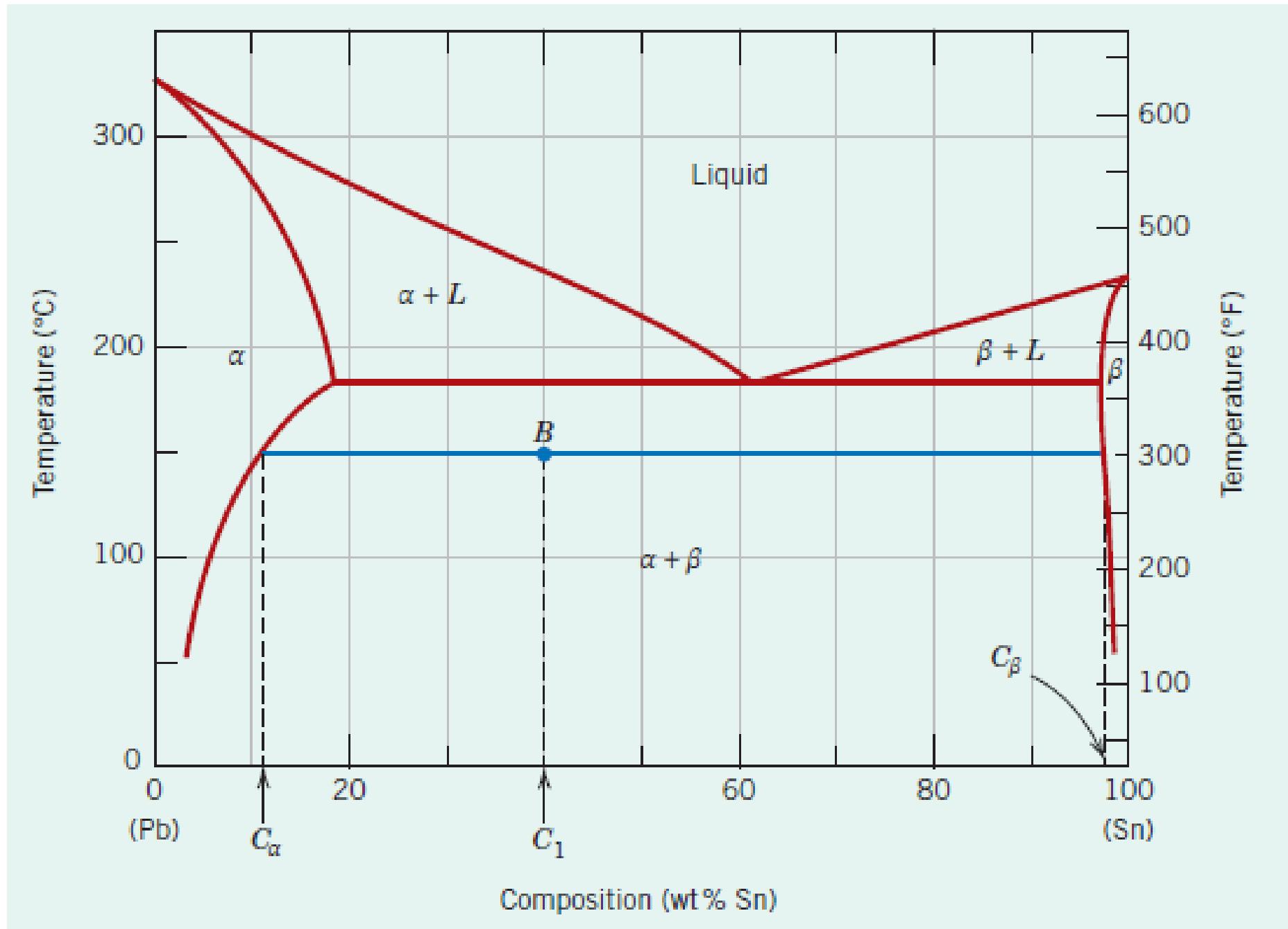
<i>Composition (wt%)</i>	<i>Solidus Temperature (°C)</i>	<i>Liquidus Temperature (°C)</i>
Solders Containing Lead		
63 Sn–37 Pb ^a	183	183
50 Sn–50 Pb	183	214
Lead-Free Solders		
99.3 Sn–0.7 Cu ^a	227	227
96.5 Sn–3.5 Ag ^a	221	221
95.5 Sn–3.8 Ag–0.7 Cu	217	220
91.8 Sn–3.4 Ag–4.8 Bi	211	213
97.0 Sn–2.0 Cu–0.85 Sb–0.2 Ag	219	235

^a Stands for eutectic systems.

Determination of Phases Present and Computation of Phase Compositions

For a 40 wt% Sn–60 wt% Pb alloy at 150°C (300°F), **(a)** what phase(s) is (are) present? **(b)** What is (are) the composition(s) of the phase(s)?





Relative Phase Amount Determinations—Mass and Volume Fractions

Calculate the relative amount of each phase present in terms of (a) mass fraction and (b) volume fraction. At 150°C, take the densities of Pb and Sn to be 11.35 and 7.29 g/cm₃, respectively.

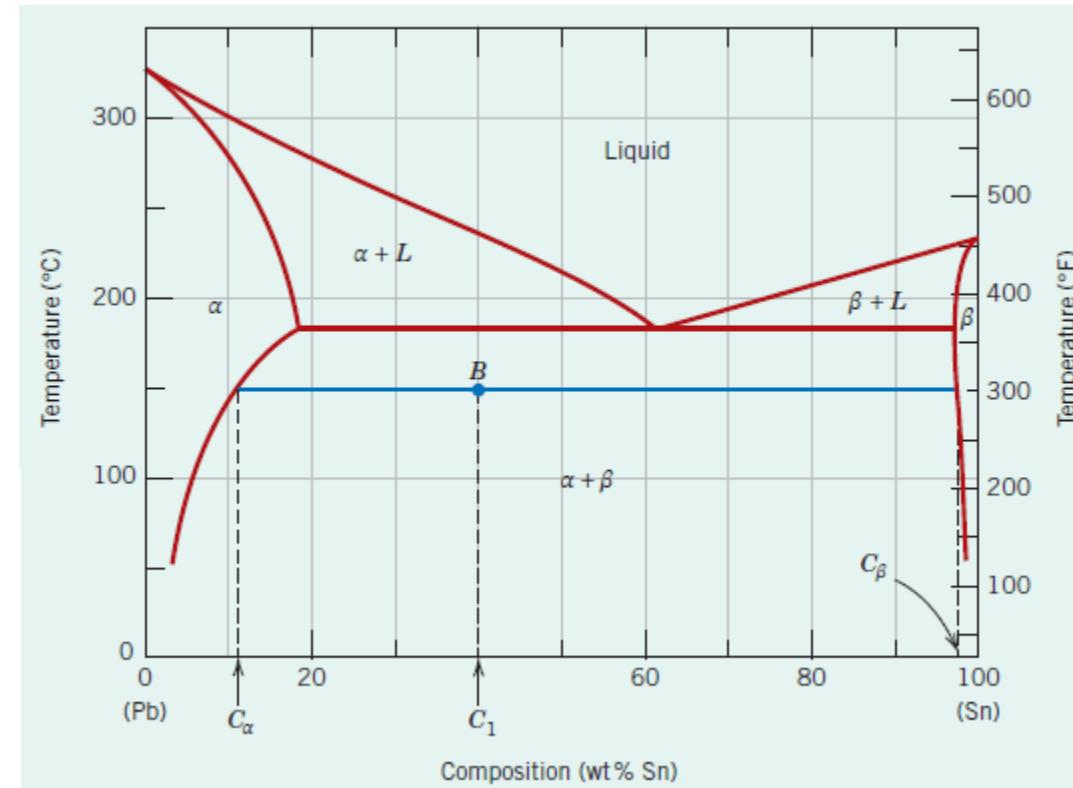
$$W_{\alpha} = \frac{C_{\beta} - C_1}{C_{\beta} - C_{\alpha}} = \frac{98 - 40}{98 - 11} = 0.67$$

$$W_{\beta} = \frac{C_1 - C_{\alpha}}{C_{\beta} - C_{\alpha}} = \frac{40 - 11}{98 - 11} = 0.33$$

$$V_{\alpha} = \frac{\frac{W_{\alpha}}{\rho_{\alpha}}}{\frac{W_{\alpha}}{\rho_{\alpha}} + \frac{W_{\beta}}{\rho_{\beta}}}$$

$$V_{\beta} = \frac{\frac{W_{\beta}}{\rho_{\beta}}}{\frac{W_{\alpha}}{\rho_{\alpha}} + \frac{W_{\beta}}{\rho_{\beta}}}$$

$$\rho_{\text{ave}} = \frac{100}{\frac{C_1}{\rho_1} + \frac{C_2}{\rho_2}}$$



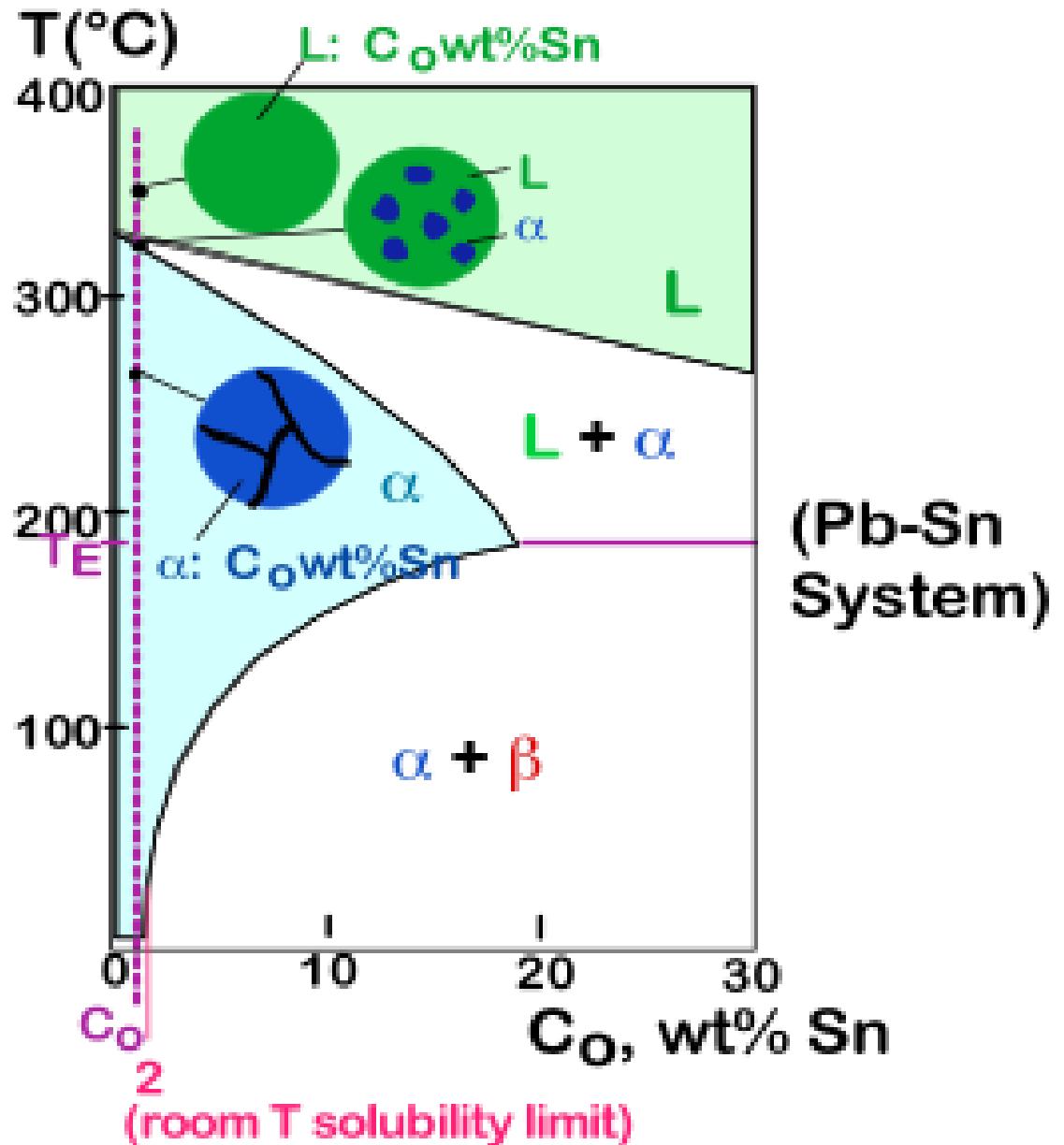
$$\rho_{\alpha} = \frac{100}{\frac{11}{7.29 \text{ g/cm}^3} + \frac{89}{11.35 \text{ g/cm}^3}} = 10.69 \text{ g/cm}^3$$

$$\begin{aligned} \rho_{\beta} &= \frac{100}{\frac{C_{\text{Sn}(\beta)}}{\rho_{\text{Sn}}} + \frac{C_{\text{Pb}(\beta)}}{\rho_{\text{Pb}}}} \\ &= \frac{100}{\frac{98}{7.29 \text{ g/cm}^3} + \frac{2}{11.35 \text{ g/cm}^3}} = 7.34 \text{ g/cm}^3 \end{aligned}$$

$$\begin{aligned} V_{\alpha} &= \frac{\frac{W_{\alpha}}{\rho_{\alpha}}}{\frac{W_{\alpha}}{\rho_{\alpha}} + \frac{W_{\beta}}{\rho_{\beta}}} \\ &= \frac{\frac{0.67}{10.69 \text{ g/cm}^3}}{\frac{0.67}{10.69 \text{ g/cm}^3} + \frac{0.33}{7.34 \text{ g/cm}^3}} = 0.58 \\ V_{\beta} &= \frac{\frac{W_{\beta}}{\rho_{\beta}}}{\frac{W_{\alpha}}{\rho_{\alpha}} + \frac{W_{\beta}}{\rho_{\beta}}} \\ &= \frac{\frac{0.33}{7.34 \text{ g/cm}^3}}{\frac{0.67}{10.69 \text{ g/cm}^3} + \frac{0.33}{7.34 \text{ g/cm}^3}} = 0.42 \end{aligned}$$

MICROSTRUCTURES IN EUTECTIC SYSTEMS-I

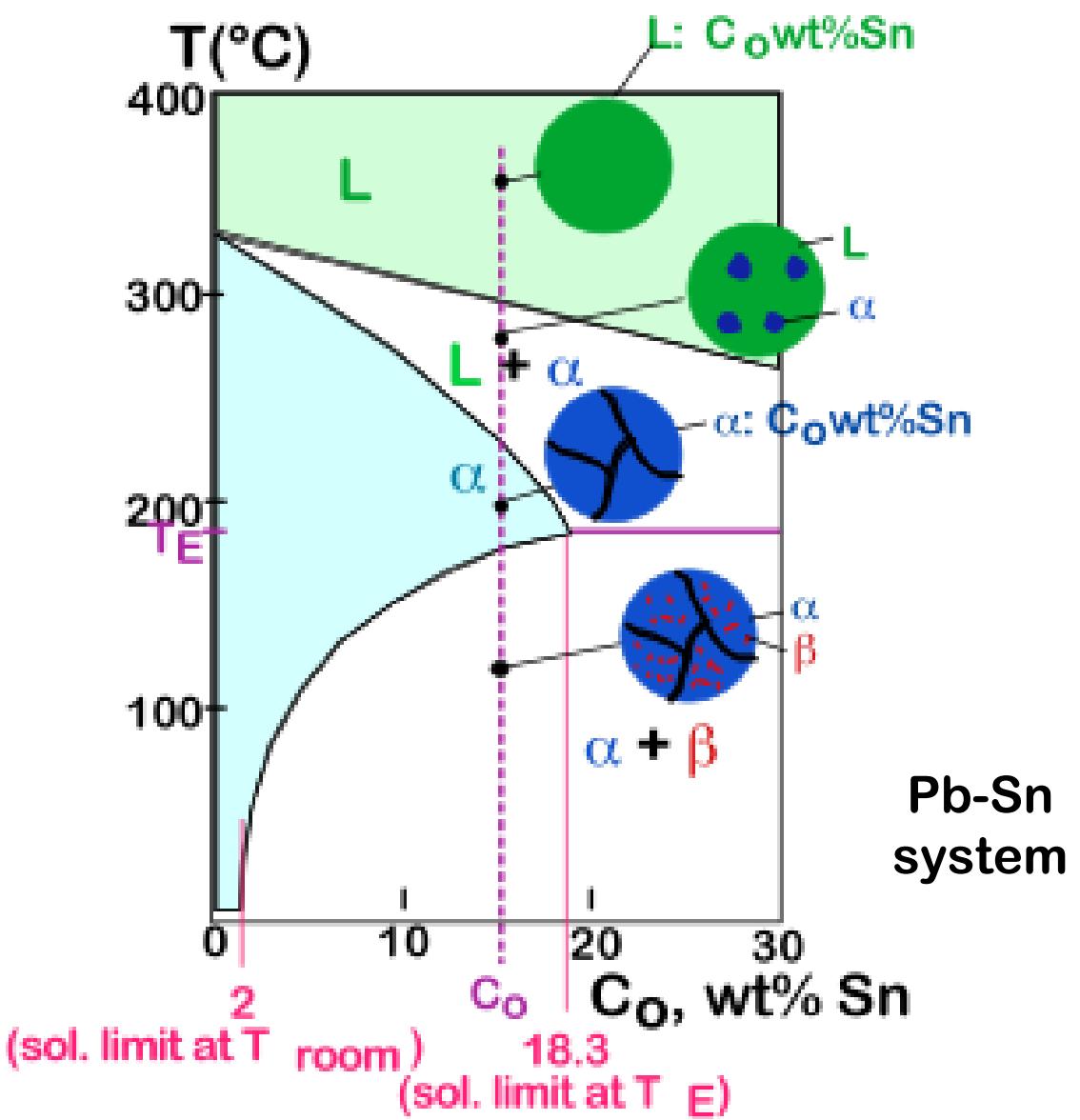
- $C_o < 2\text{wt\%Sn}$
- Result:
 - polycrystal of α grains.



MICROSTRUCTURES IN EUTECTIC SYSTEMS-II

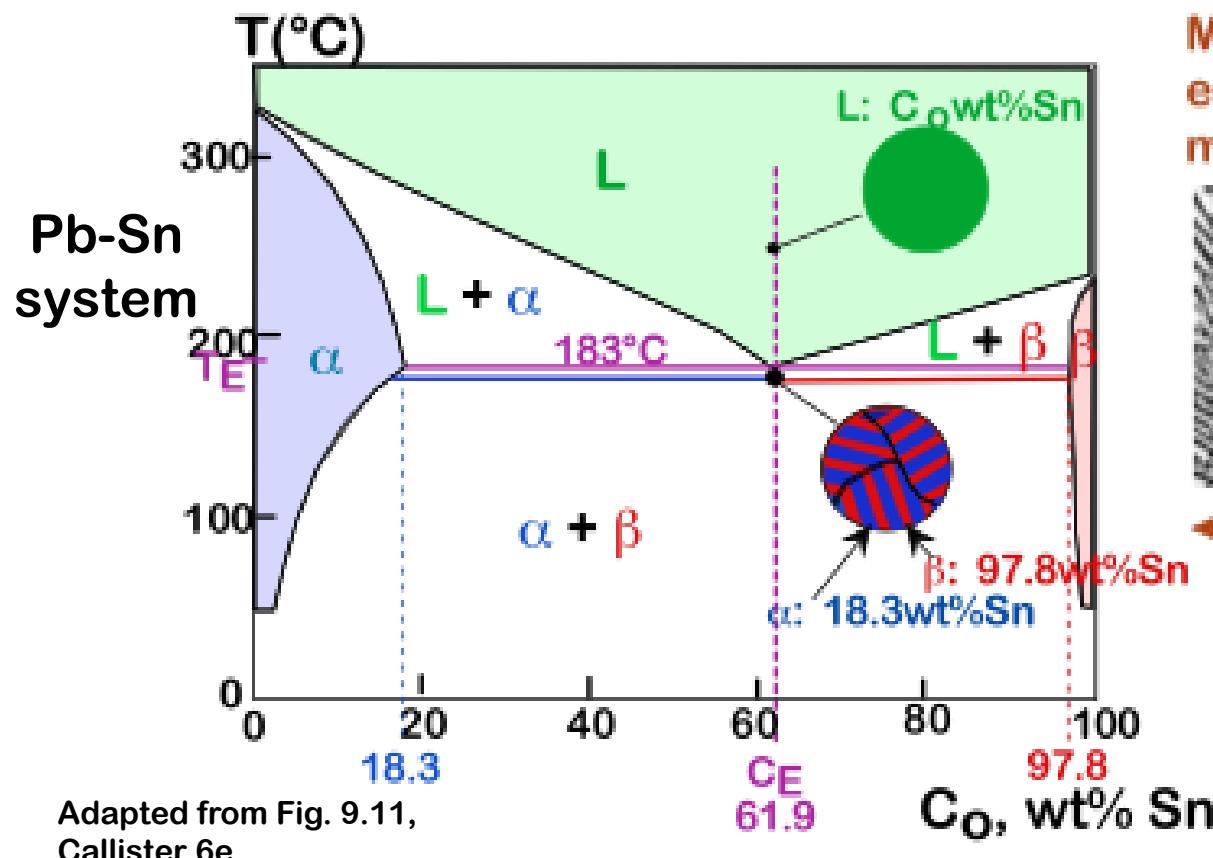
- $2\text{wt\%Sn} < C_o < 18.3\text{wt\%Sn}$
- Result:
 - α polycrystal with fine β crystals.

Adapted from Fig. 9.10,
Callister 6e.

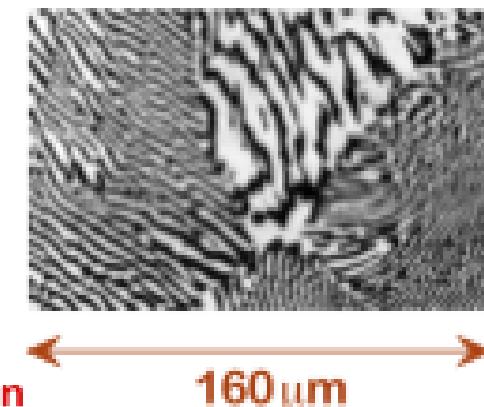


MICROSTRUCTURES IN EUTECTIC SYSTEMS-III

- $C_o = C_E$ (Eutectic composition)
- Result: Eutectic microstructure
--alternating layers of α and β crystals.

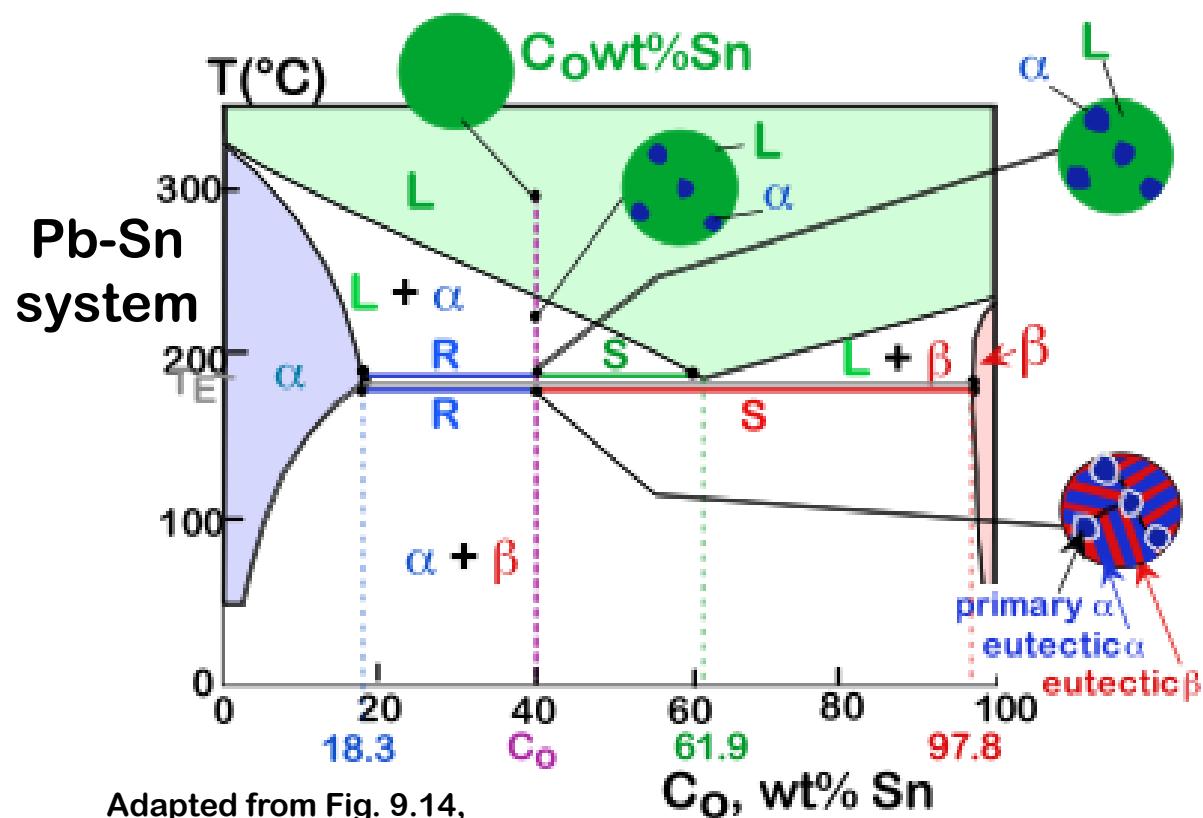


Micrograph of Pb-Sn
eutectic
microstructure



MICROSTRUCTURES IN EUTECTIC SYSTEMS-IV

- $18.3\text{wt\%Sn} < C_0 < 61.9\text{wt\%Sn}$
- Result: α crystals and a eutectic microstructure



- Just above T_E:

$$C_\alpha = 18.3\text{wt\%Sn}$$

$$C_L = 61.9\text{wt\%Sn}$$

$$W_\alpha = \frac{S}{R+S} = 50\text{wt\%}$$

$$W_L = (1-W_\alpha) = 50\text{wt\%}$$

- Just below T_E:

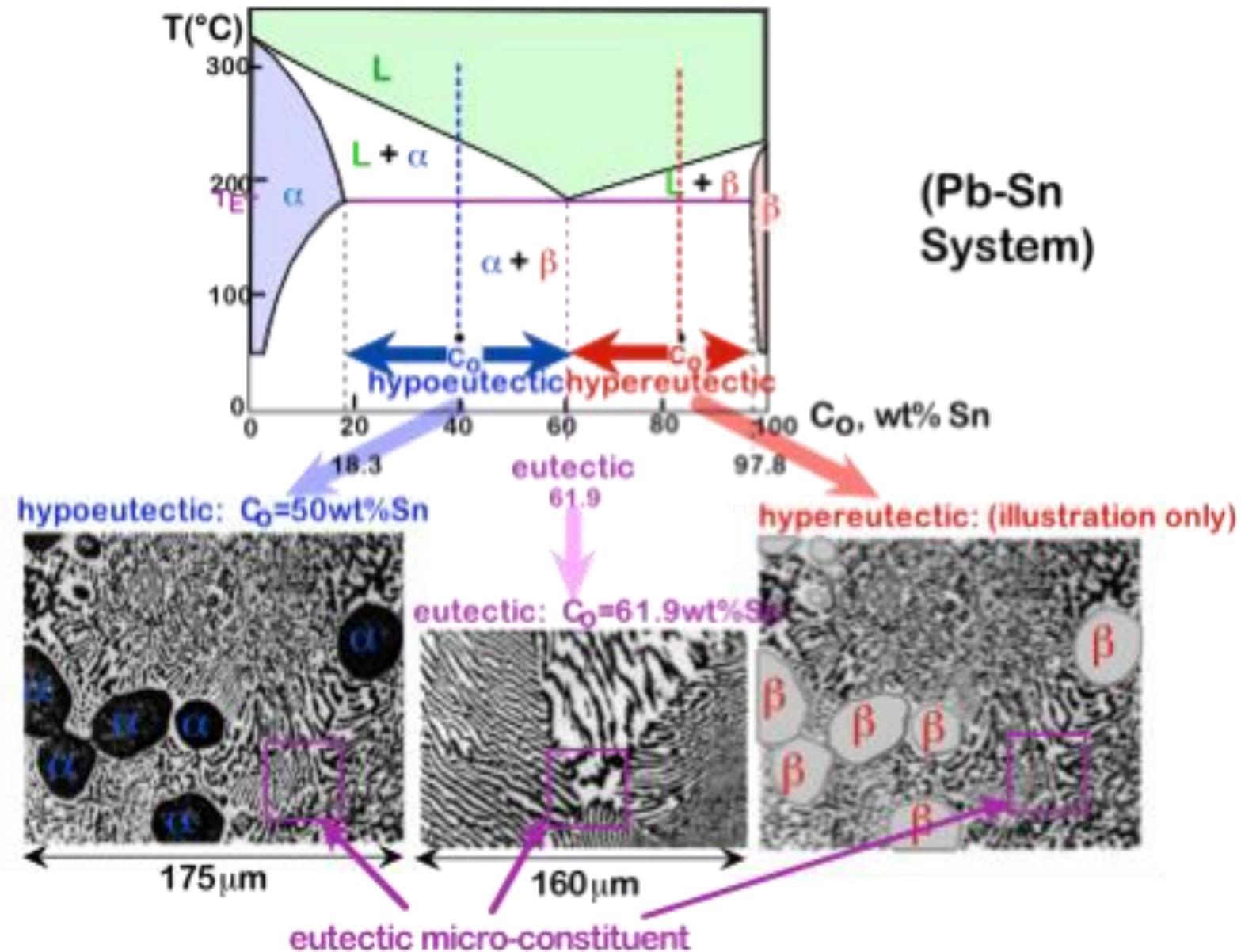
$$C_\alpha = 18.3\text{wt\%Sn}$$

$$C_\beta = 97.8\text{wt\%Sn}$$

$$W_\alpha = \frac{S}{R+S} = 73\text{wt\%}$$

$$W_\beta = 27\text{wt\%}$$

HYPOTECTIC & HYPEREUTECTIC



IRON-CARBON (Fe-C) PHASE DIAGRAM

1. Pure iron: 3 solid phases

- BCC ferrite (α)
- FCC Austenite (γ)
- BCC (δ)

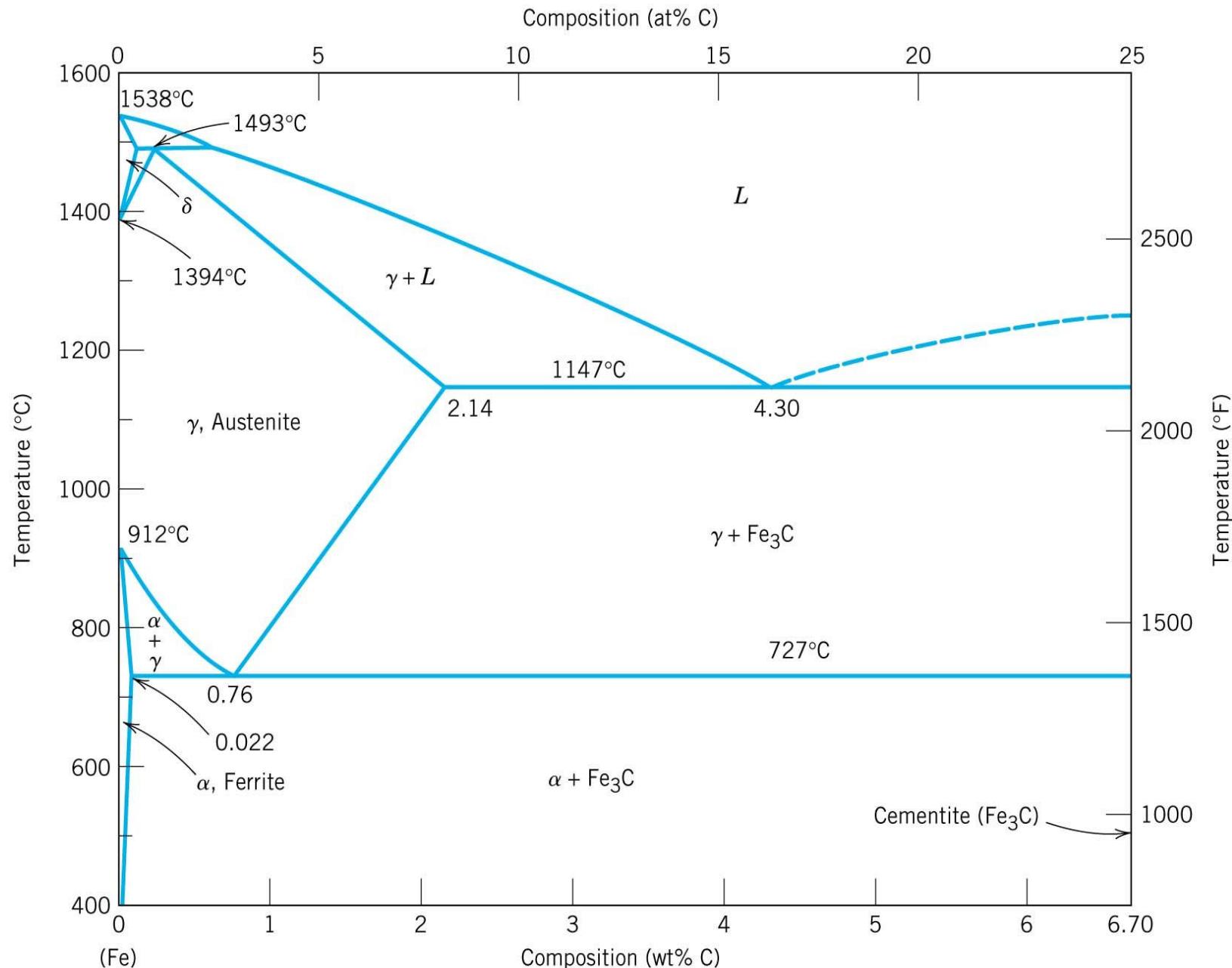
2. Beyond 6.7% C \rightarrow cementite (Fe_3C)

3. Eutectic: 4.3% C

- $\text{L} \leftrightarrow \gamma + \text{Fe}_3\text{C}$
- ($\text{L} \leftrightarrow \text{solid} + \text{solid}$)

4. Eutectoid: 0.76% C

- $\gamma \leftrightarrow \alpha + \text{Fe}_3\text{C}$
- ($\text{solid} \leftrightarrow \text{solid} + \text{solid}$)



Classification of Ferrous Alloys based on carbon content

Commercially

1. Iron: contains less than 0.008 wt% C
2. Steels: contain between 0.008 and 2.14 wt% C.
3. Cast irons: contain between 2.14 and 6.70 wt% C.

Fe-C PHASE DIAGRAM: EUTECTOID POINT

Figure 9.26 Schematic representations of the microstructures for an iron-carbon alloy of eutectoid composition (0.76 wt% C) above and below the eutectoid temperature.

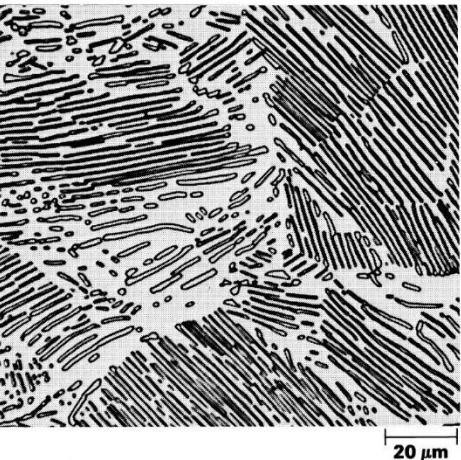
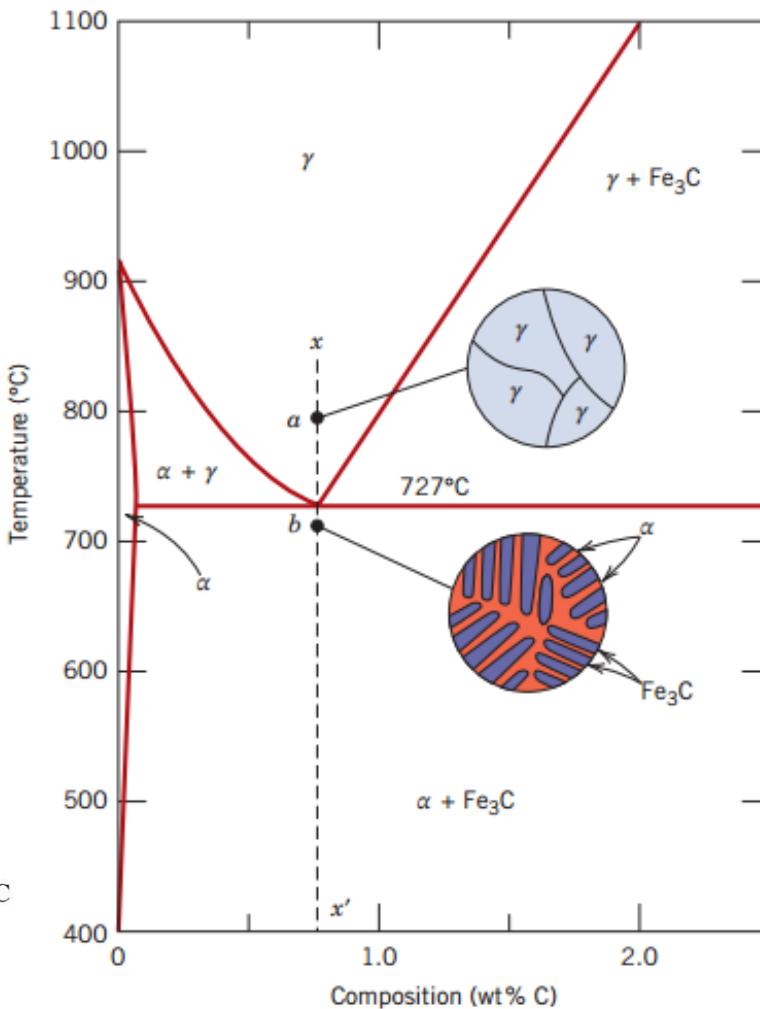
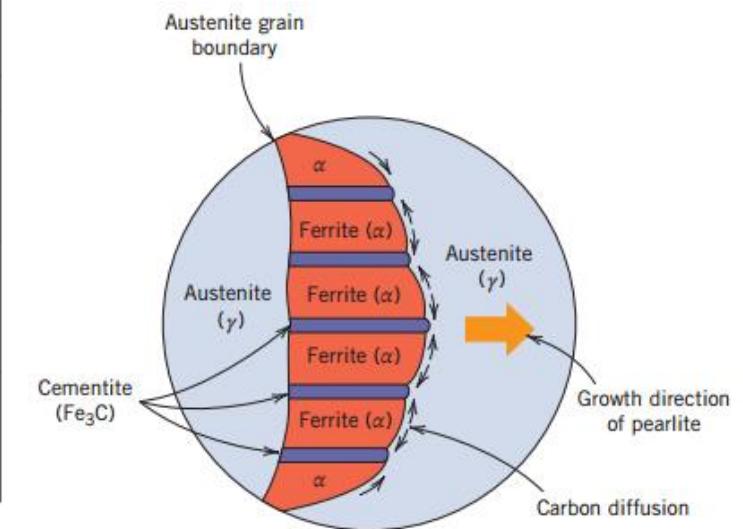


FIGURE 9.24 Photomicrograph of a eutectoid steel showing the pearlite microstructure consisting of alternating layers of α ferrite (the light phase) and Fe_3C (thin layers most of which appear dark). 500 \times . (Reproduced with permission from *Metals Handbook*, 9th edition, Vol. 9, *Metallography and Microstructures*, American Society for Metals, Materials Park, OH, 1985.)



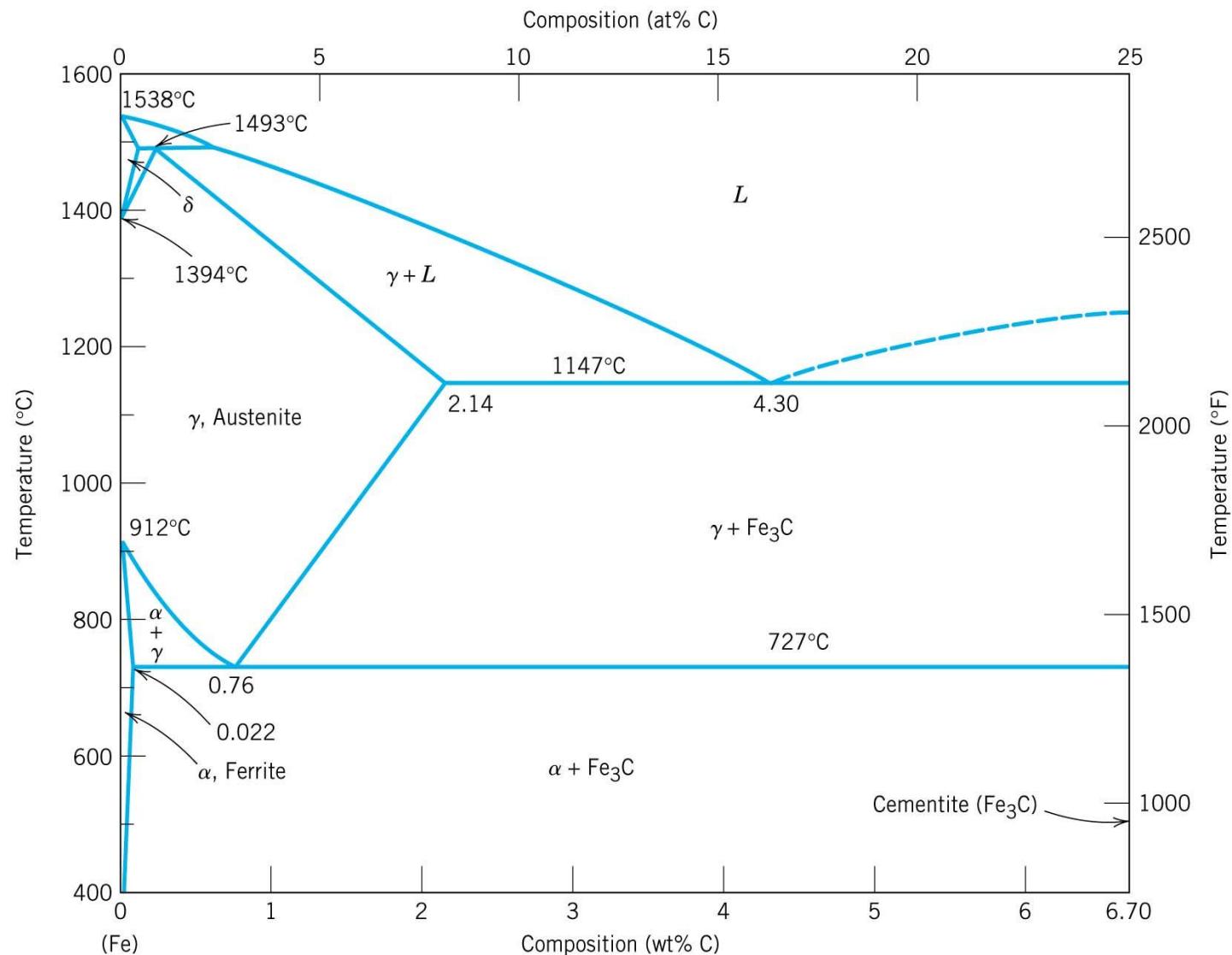
Pearlite microstructure:
Just below the eutectoid point



The solubility C in γ Austenite is approximately 100 times greater than the maximum for BCC ferrite because the FCC octahedral sites are larger than the BCC tetrahedral sites.

EUTECTOID POINT: LEVER RULE

- Just below the eutectoid point:
- $W_{\alpha} = (6.7 - 0.76) / (6.7 - 0.022)$
= 89%
- $W_{Fe_3C} = (0.76 - 0.022) / (6.7 - 0.022)$
= 11%



HYPOEUTECTOID STEEL

FIGURE 9.27
Photomicrograph of a 0.38 wt% C steel having a microstructure consisting of pearlite and proeutectoid ferrite. 635 \times . (Photomicrograph courtesy of Republic Steel Corporation.)

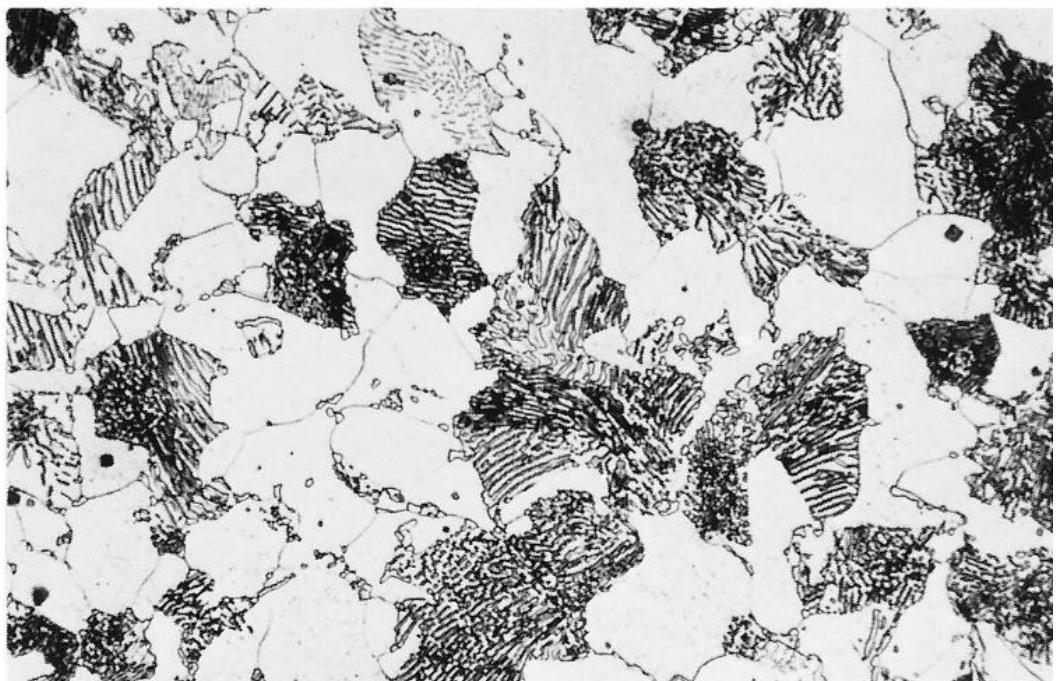
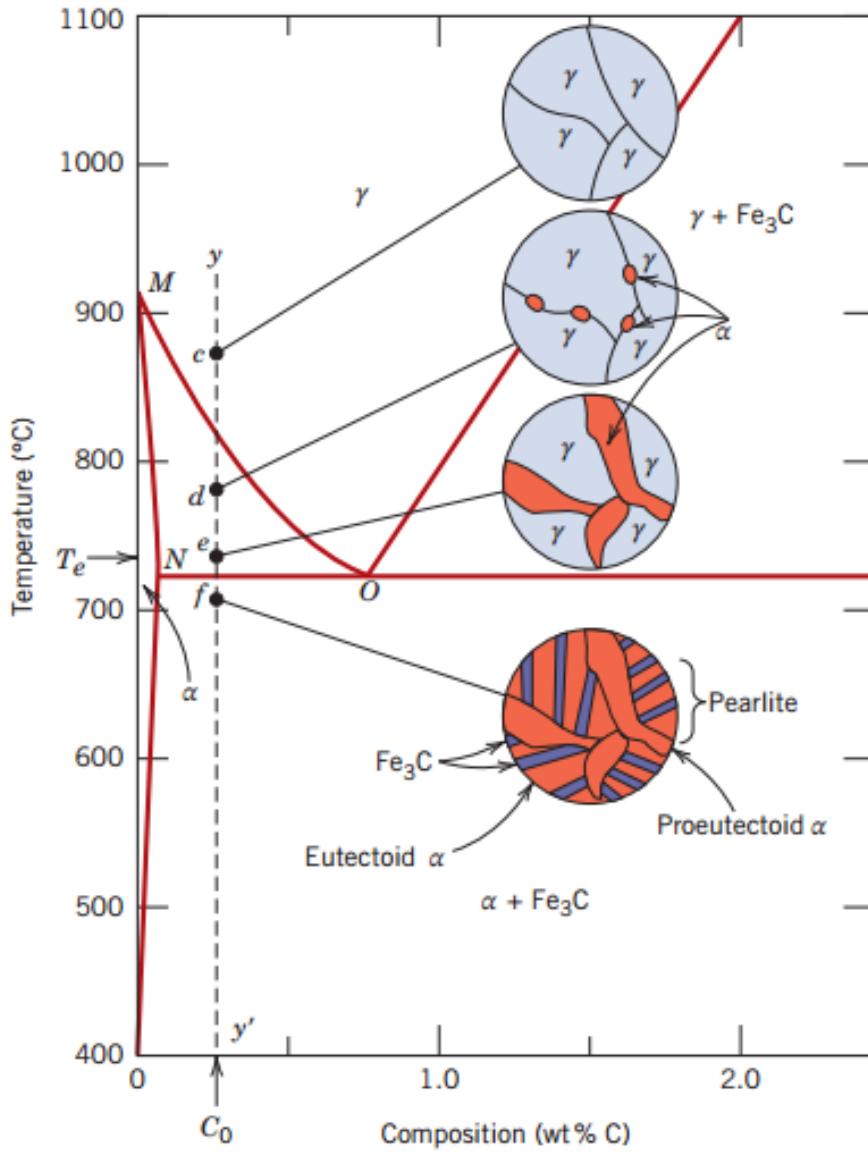


Figure 9.29 Schematic representations of the microstructures for an iron-carbon alloy of hypoeutectoid composition C_0 (containing less than 0.76 wt% C) as it is cooled from within the austenite phase region to below the eutectoid temperature.



HYPEREUTECTOID STEEL

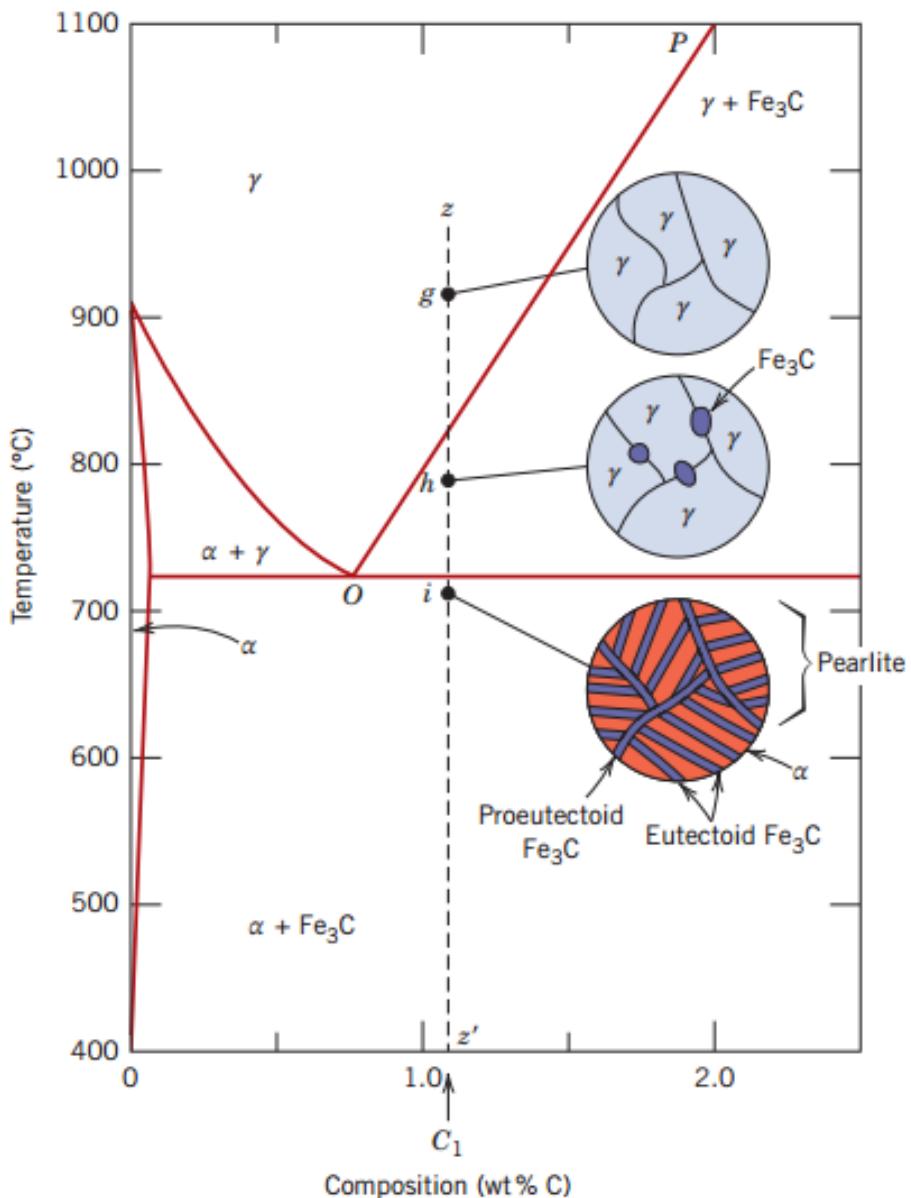


Figure 9.32 Schematic representations of the microstructures for an iron–carbon alloy of hypereutectoid composition C_1 (containing between 0.76 and 2.14 wt % C) as it is cooled from within the austenite-phase region to below the eutectoid temperature.



FIGURE 9.30 Photomicrograph of a 1.4 wt% C steel having a microstructure consisting of a white proeutectoid cementite network surrounding the pearlite colonies. 1000 \times . (Copyright 1971 by United States Steel Corporation.)

HYPOEUTECTOID

$$W_p = \frac{T}{T+U}$$

$$= \frac{C'_0 - 0.022}{0.76 - 0.022} = \frac{C'_0 - 0.022}{0.74}$$

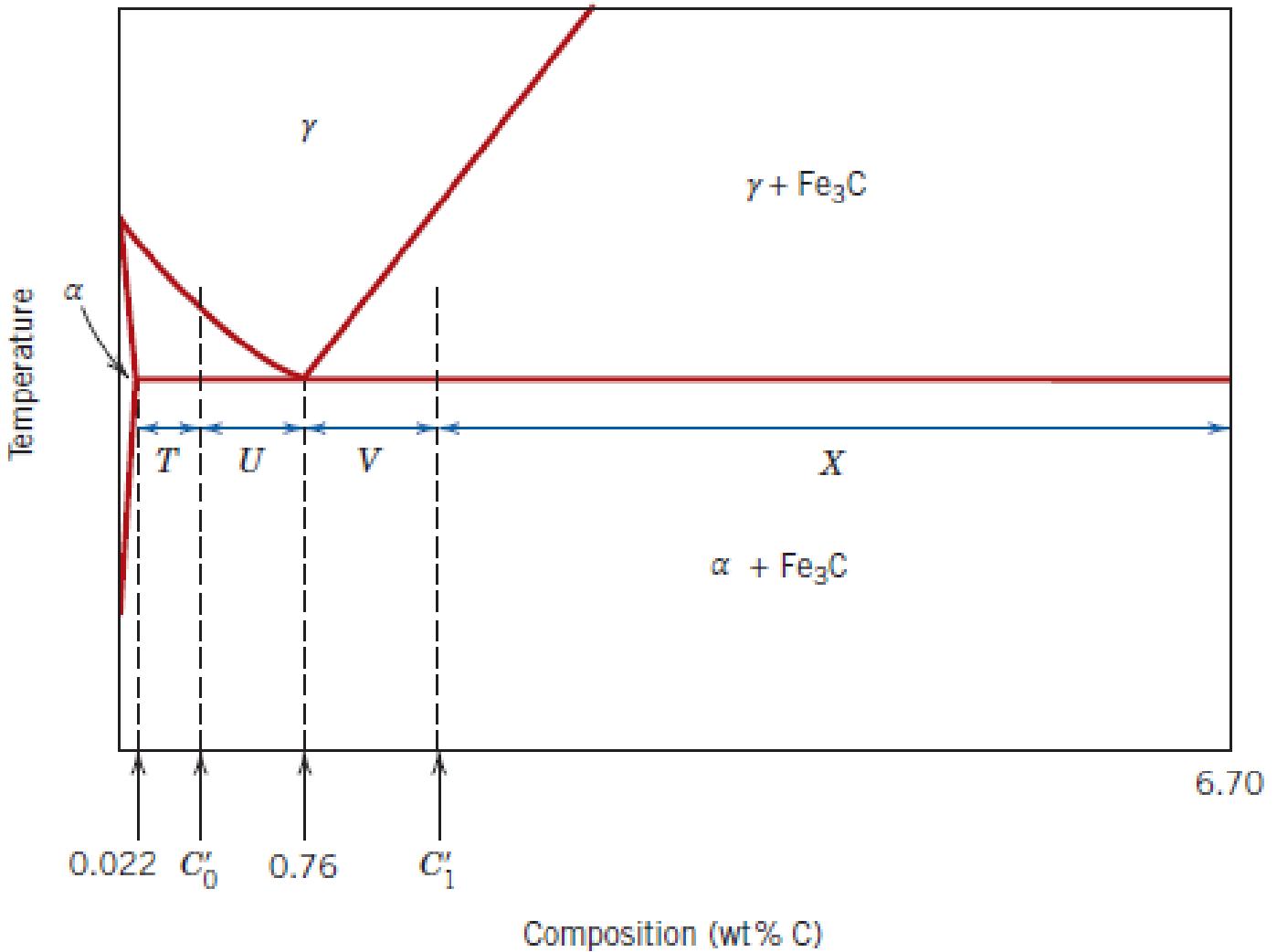
$$W_{\alpha'} = \frac{U}{T+U}$$

$$= \frac{0.76 - C'_0}{0.76 - 0.022} = \frac{0.76 - C'_0}{0.74}$$

HYPEREUTECTOID

$$W_p = \frac{X}{V+X} = \frac{6.70 - C'_1}{6.70 - 0.76} = \frac{6.70 - C'_1}{5.94}$$

$$W_{Fe_3C} = \frac{V}{V+X} = \frac{C'_1 - 0.76}{6.70 - 0.76} = \frac{C'_1 - 0.76}{5.94}$$

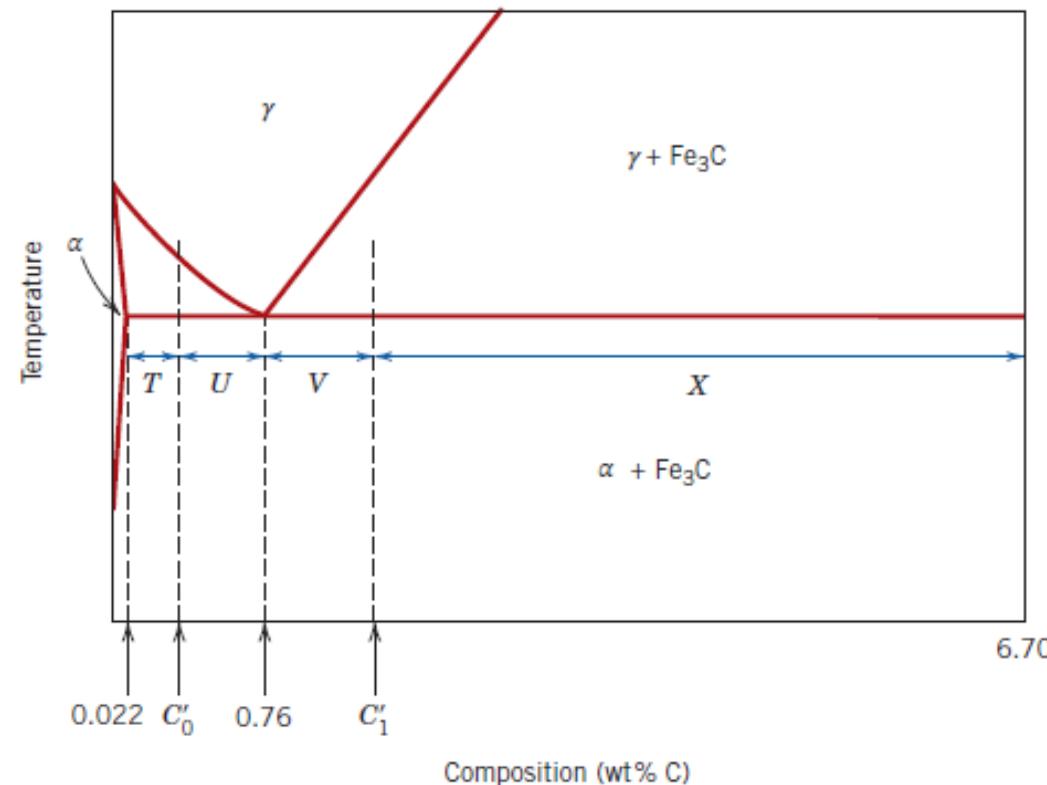


Proeutectoid (ferrite and cementite) and pearlite microconstituents for hypoeutectoid C'_0 and hypereutectoid C'_1 compositions.

Determination of Relative Amounts of Ferrite, Cementite, and Pearlite Microconstituents

For a 99.65 wt% Fe–0.35 wt% C alloy at a temperature just below the eutectoid, determine the following:

- The fractions of total ferrite and cementite phases
- The fractions of the proeutectoid ferrite and pearlite
- The fraction of eutectoid ferrite



Determination of Relative Amounts of Ferrite, Cementite, and Pearlite Microconstituents

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- The fractions of total ferrite and cementite phases
- The fractions of the proeutectoid ferrite and pearlite
- The fraction of eutectoid ferrite

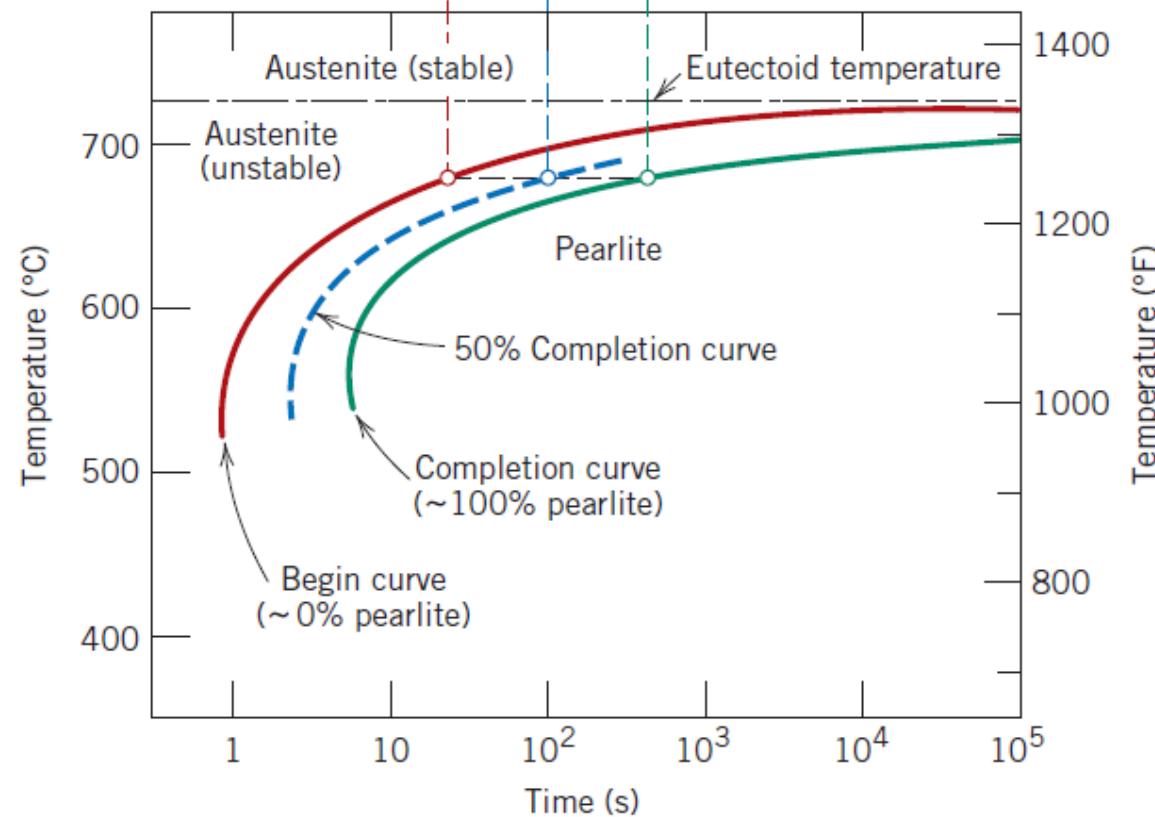
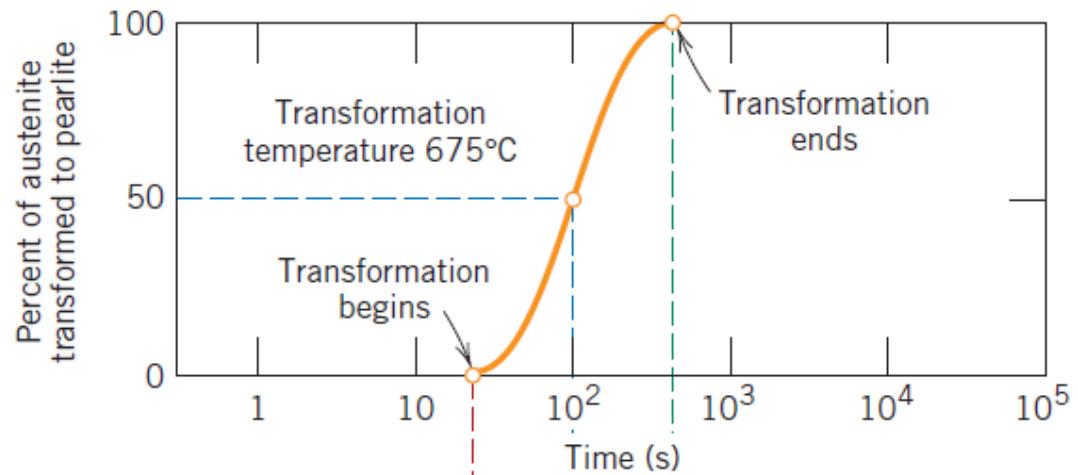
$$W_{\alpha} = \frac{6.70 - 0.35}{6.70 - 0.022} = 0.95$$

$$W_p = \frac{0.35 - 0.022}{0.76 - 0.022} = 0.44$$

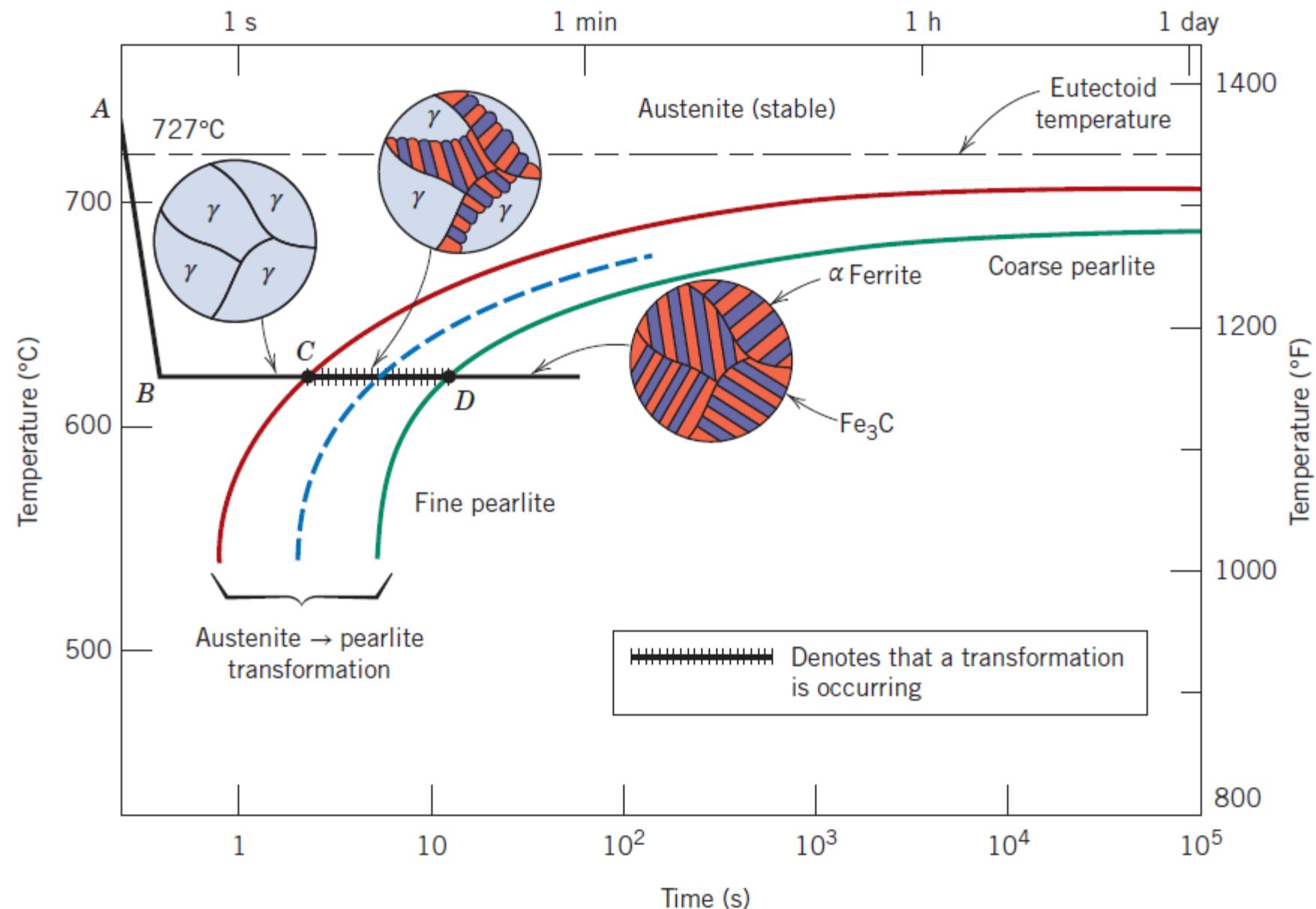
$$W_{Fe_3C} = \frac{0.35 - 0.022}{6.70 - 0.022} = 0.05$$

$$W_{\alpha'} = \frac{0.76 - 0.35}{0.76 - 0.022} = 0.56$$

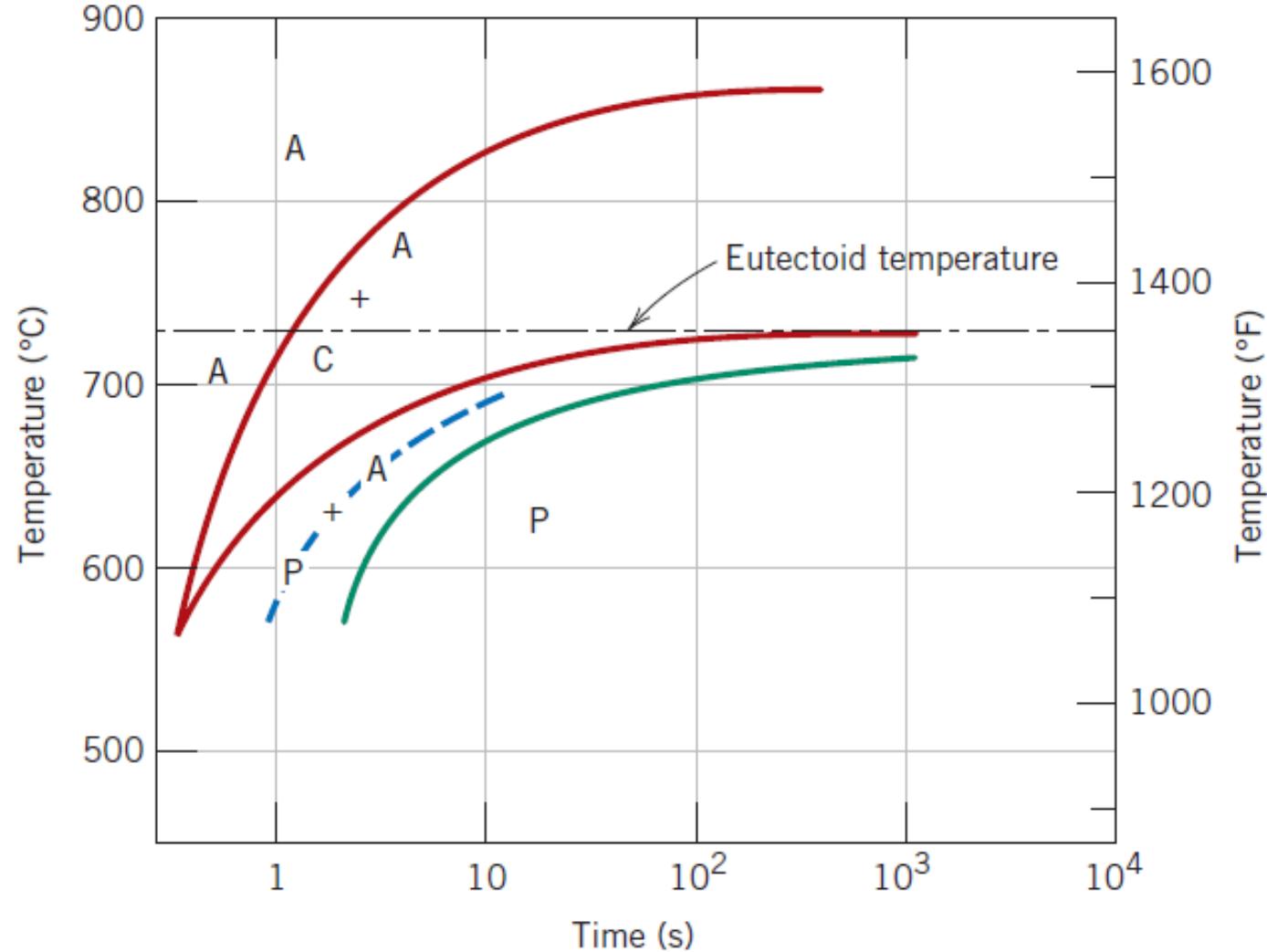
$$W_{ae} = W_{\alpha} - W_{\alpha'} = 0.95 - 0.56 = 0.39$$



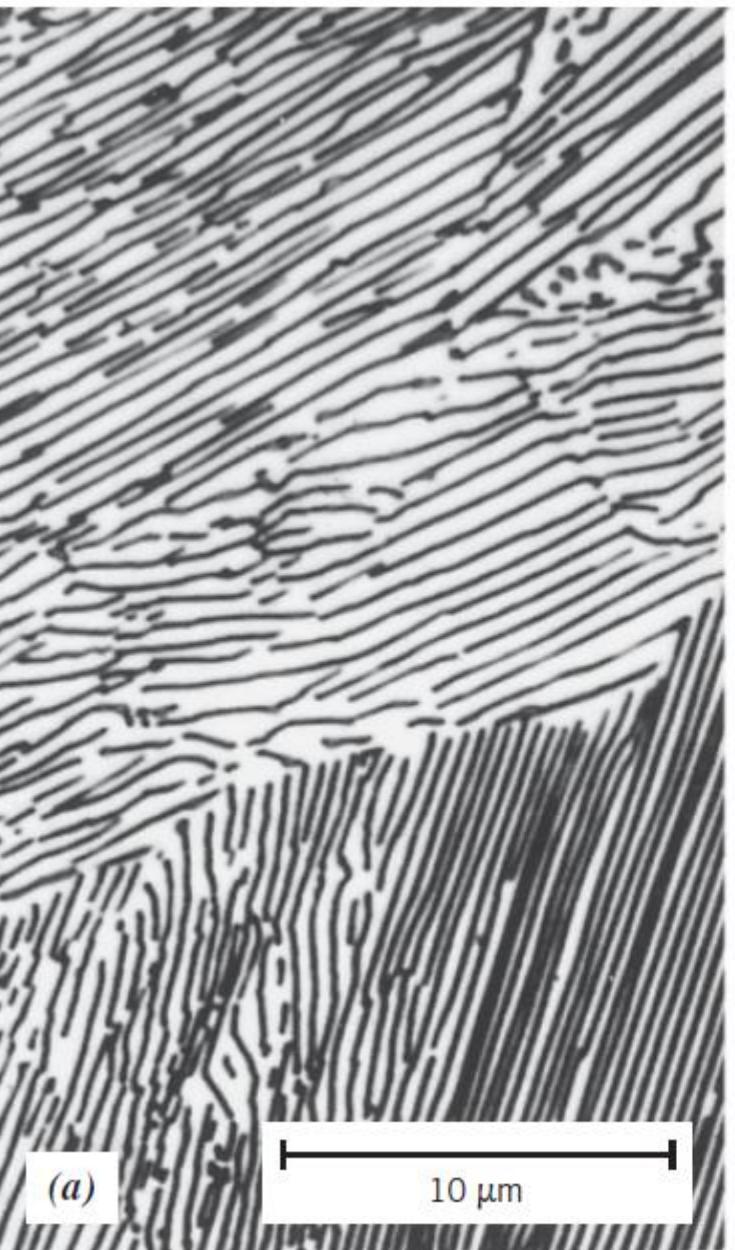
Demonstration of an
isothermal transformation
diagram



Isothermal transformation diagram for a eutectoid iron–carbon alloy, with superimposed isothermal heat treatment curve (ABCD).



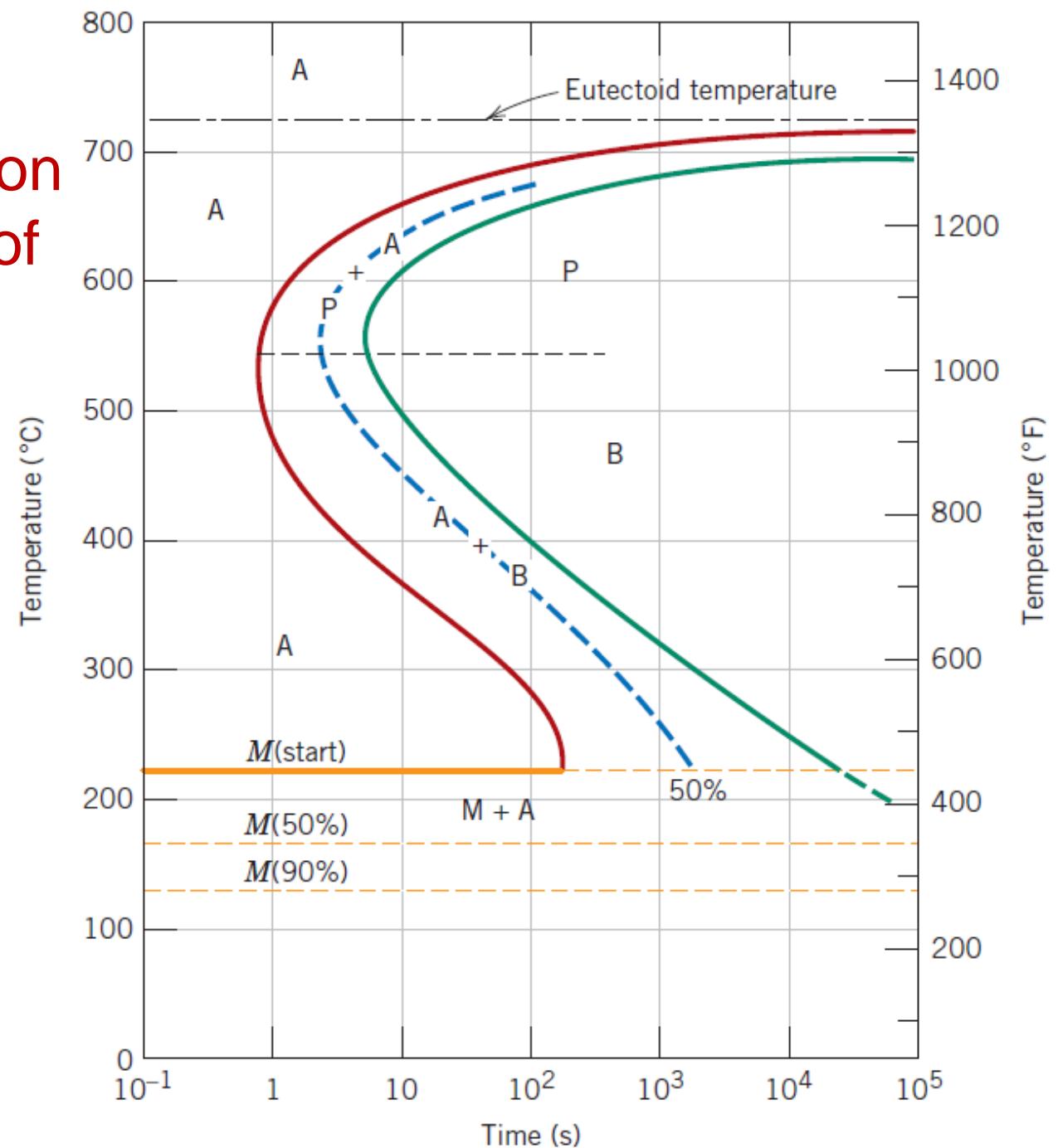
Isothermal transformation diagram for a 1.13 wt% C iron–carbon alloy:
A, austenite; C, proeutectoid cementite; P, pearlite.



Coarse and Fine Pearlite

Complete isothermal transformation diagram for an iron–carbon alloy of eutectoid composition:

- A, austenite;
- B, bainite;
- M, martensite;
- P, pearlite.



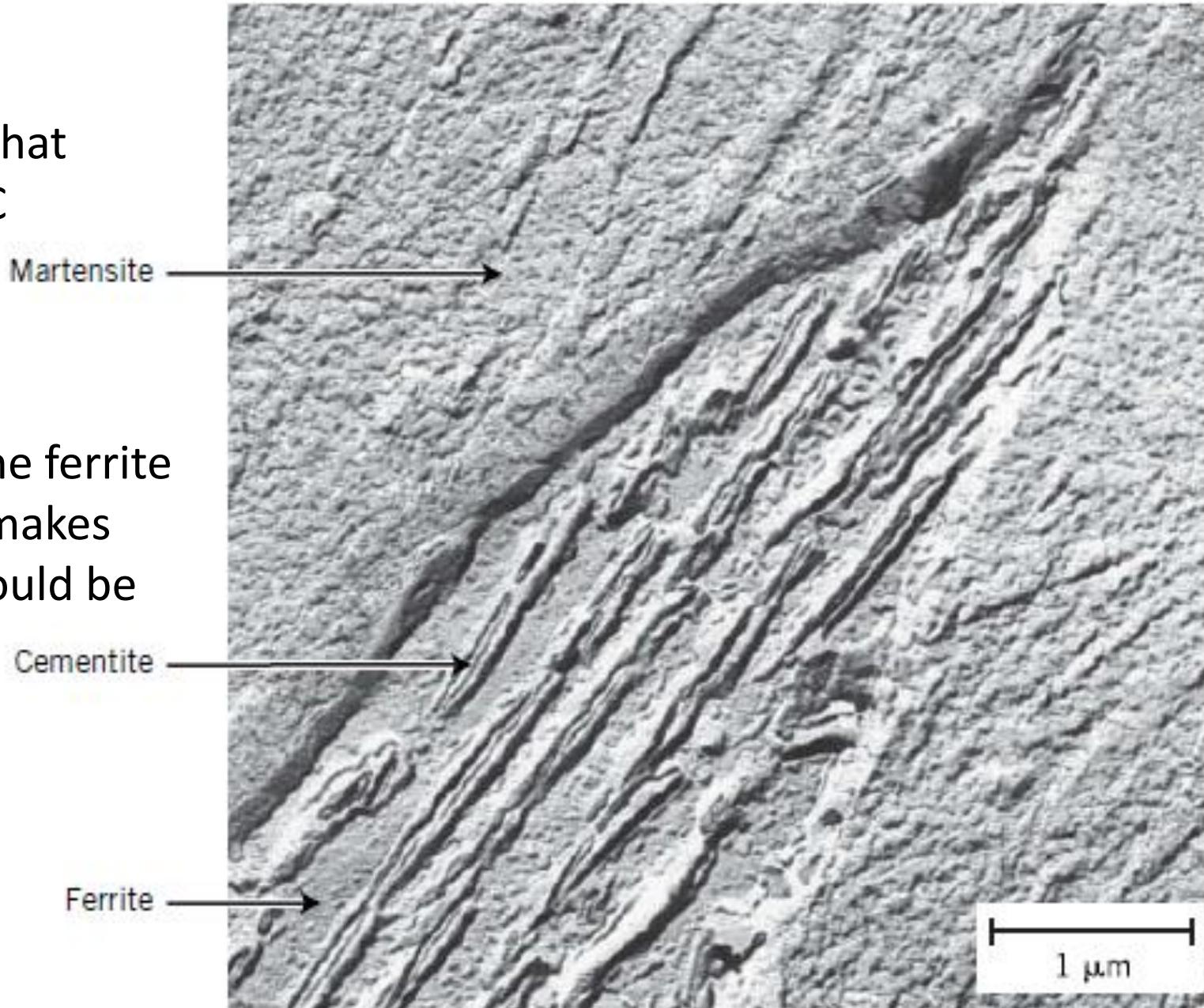
Bainite

Bainite is a plate-like microstructure that forms at temperatures of 125–550 °C

It consists of **cementite** and **dislocation-rich ferrite**.

The large density of dislocations in the ferrite the fine size of the bainite platelets, makes this ferrite harder than it normally would be

No change in composition of the phases compared with pearlite.



Martensite

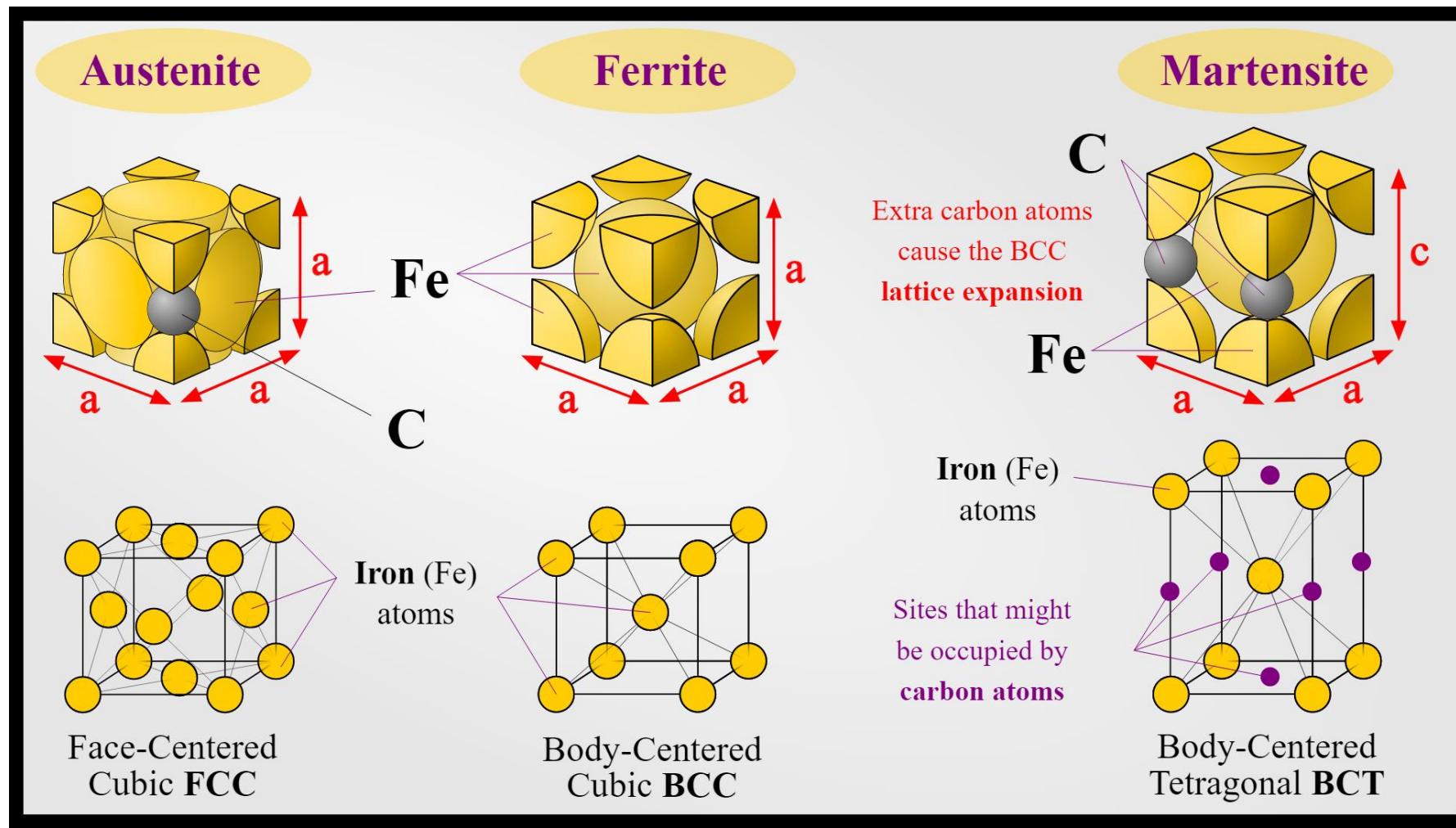
Martensite is formed in carbon steels by the rapid cooling (**quenching**) of the austenite form of iron.

At such a high cooling rate that carbon atoms do not have time to diffuse out of the crystal structure in large enough quantities to form cementite (Fe_3C).

Photomicrograph showing the martensitic microstructure. The needleshape grains are the martensite phase, and the white regions are austenite that failed to transform during the rapid quench. 1220x



10 μm

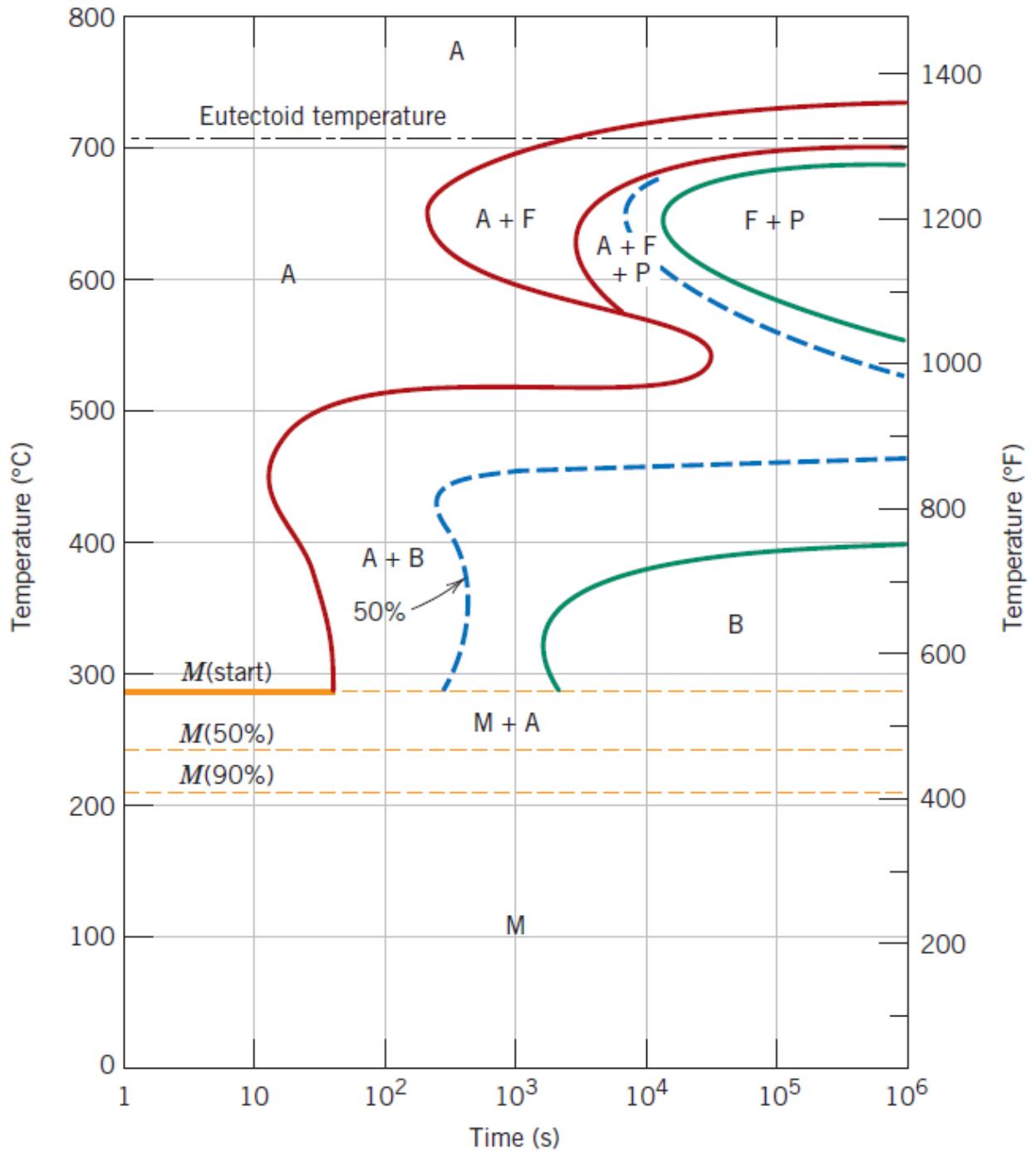


As a result of the quenching, the FCC austenite transforms to a highly strained body-centered tetragonal (BCT) form called martensite that is supersaturated with carbon.

The shear deformations that result produce a large number of dislocations, which is a primary strengthening mechanism of steels. The highest hardness of a pearlitic steel is 400 Brinell, whereas martensite can achieve 700 Brinell.[2]

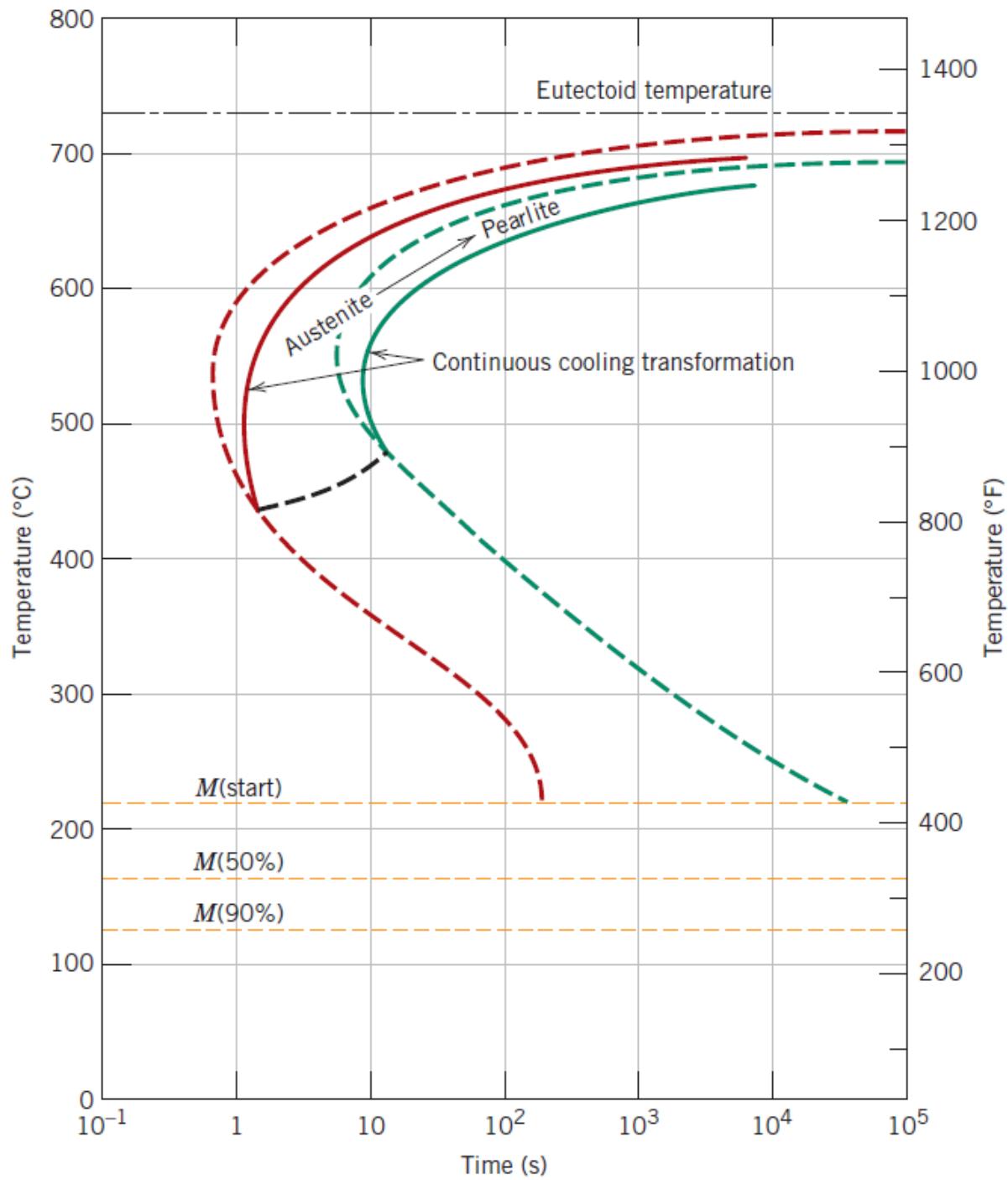
Isothermal transformation diagram for an alloy steel (4340):

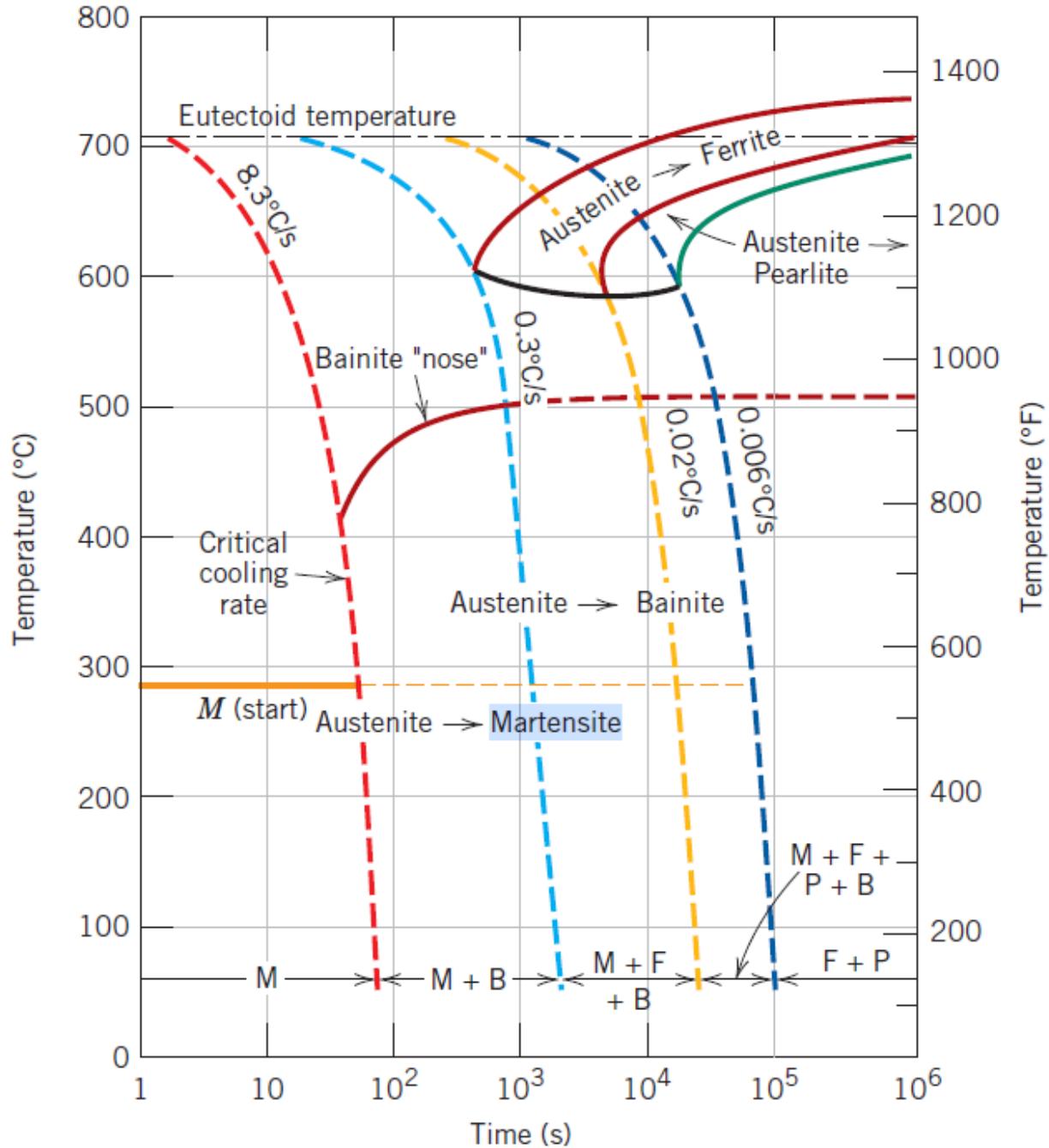
A, austenite;
B, bainite;
P, pearlite;
M, martensite;
F, proeutectoid ferrite.



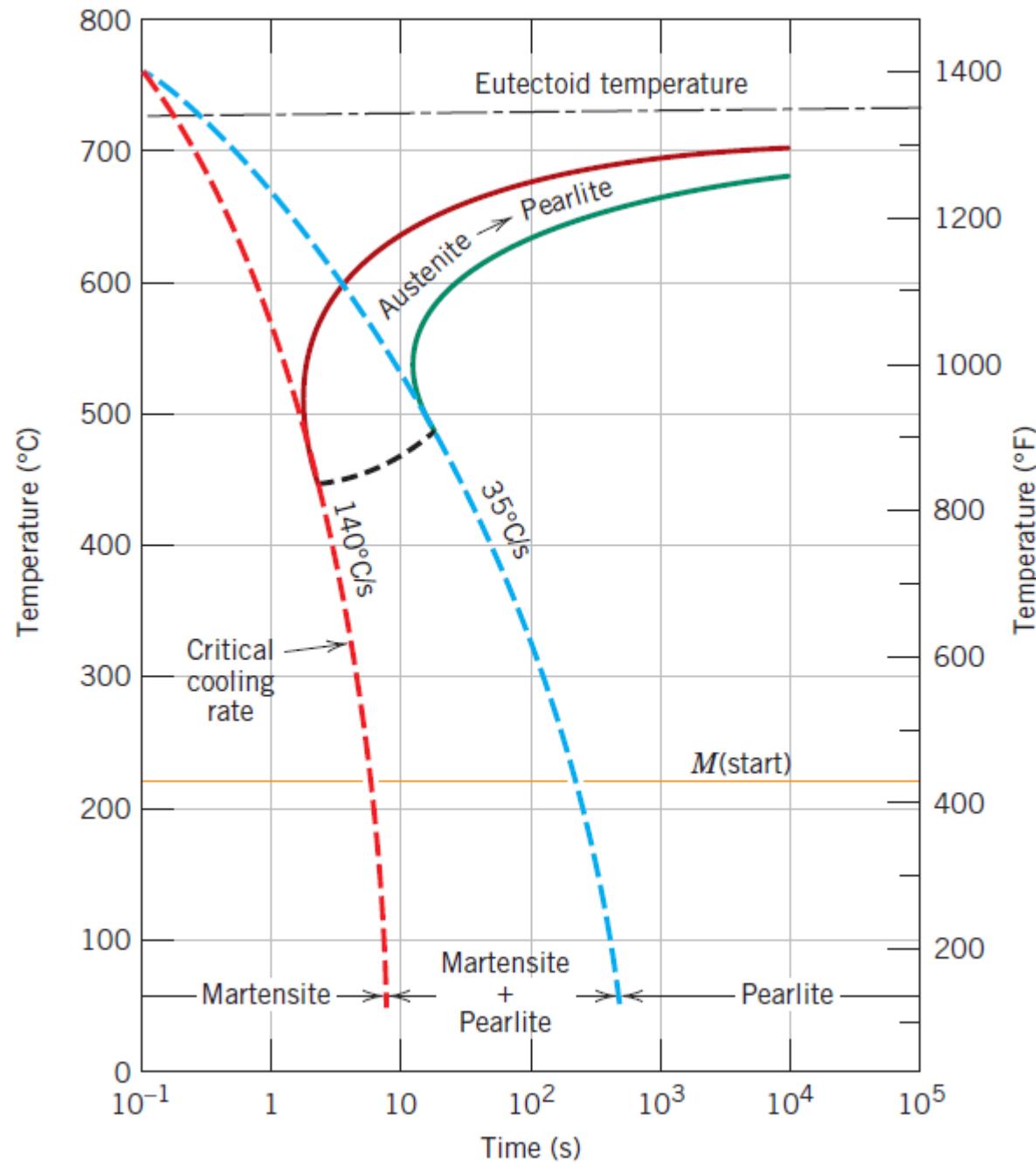
Continuous-Cooling Transformation (CCT) diagram

For continuous cooling, the time required for a reaction to begin and end is delayed. Thus the isothermal curves are shifted to longer times and lower temperatures.





Continuous-Cooling Transformation steel 4340



Continuous-Cooling Transformation Eutectoid steel Composition

Mechanical Behaviour of Iron–Carbon Alloys

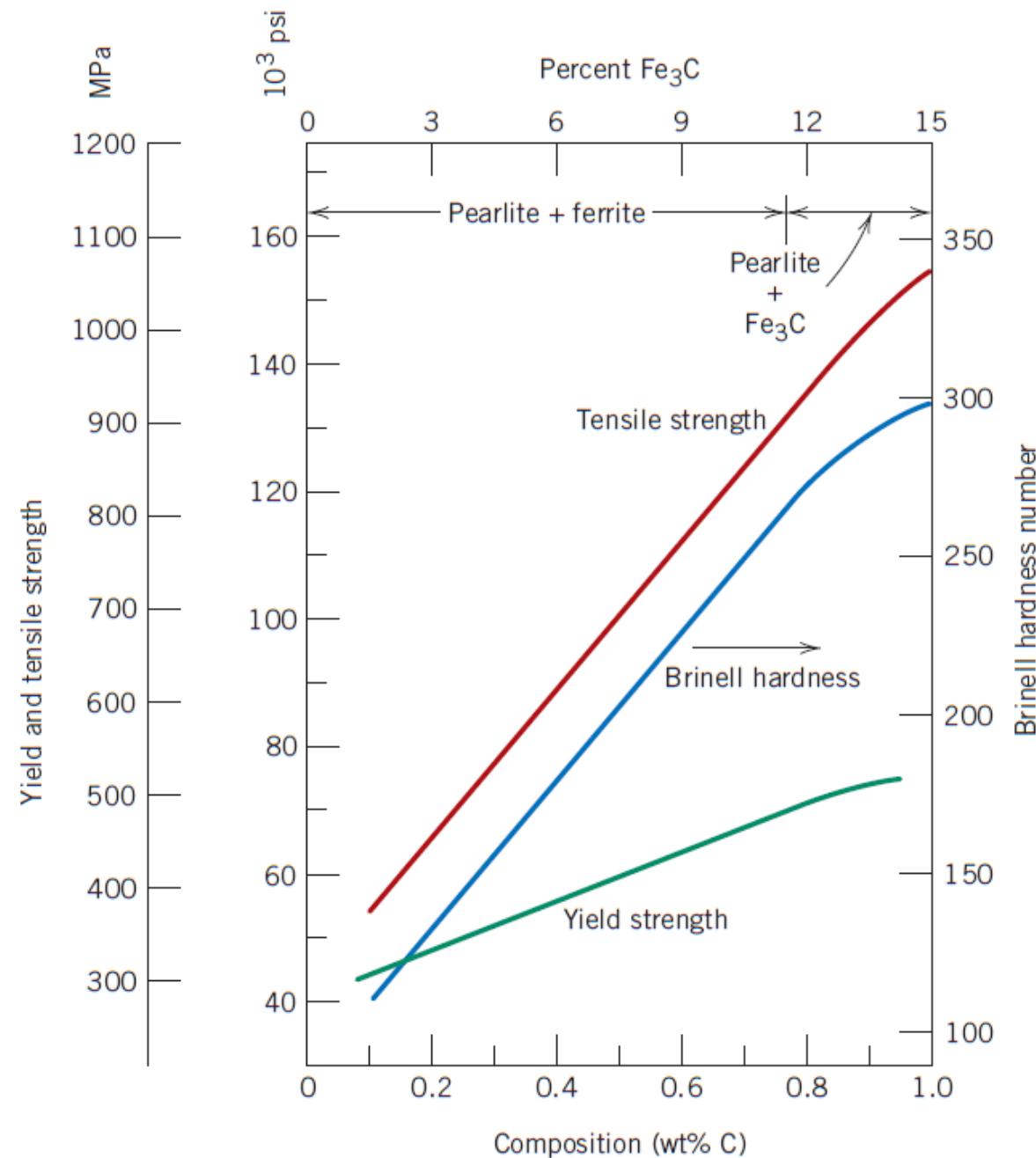
Strength – Resistance to deform permanently (plastic deformation).

Hardness – Resistance to localized plastic deformation (like dents, scratches etc).

Ductility – A measure of material's capability to undergo large plastic deformations before fracture.

Pearlite:

Increasing Fe_3C will make the material more brittle and harder.



Mechanical Behaviour of Iron–Carbon Alloys

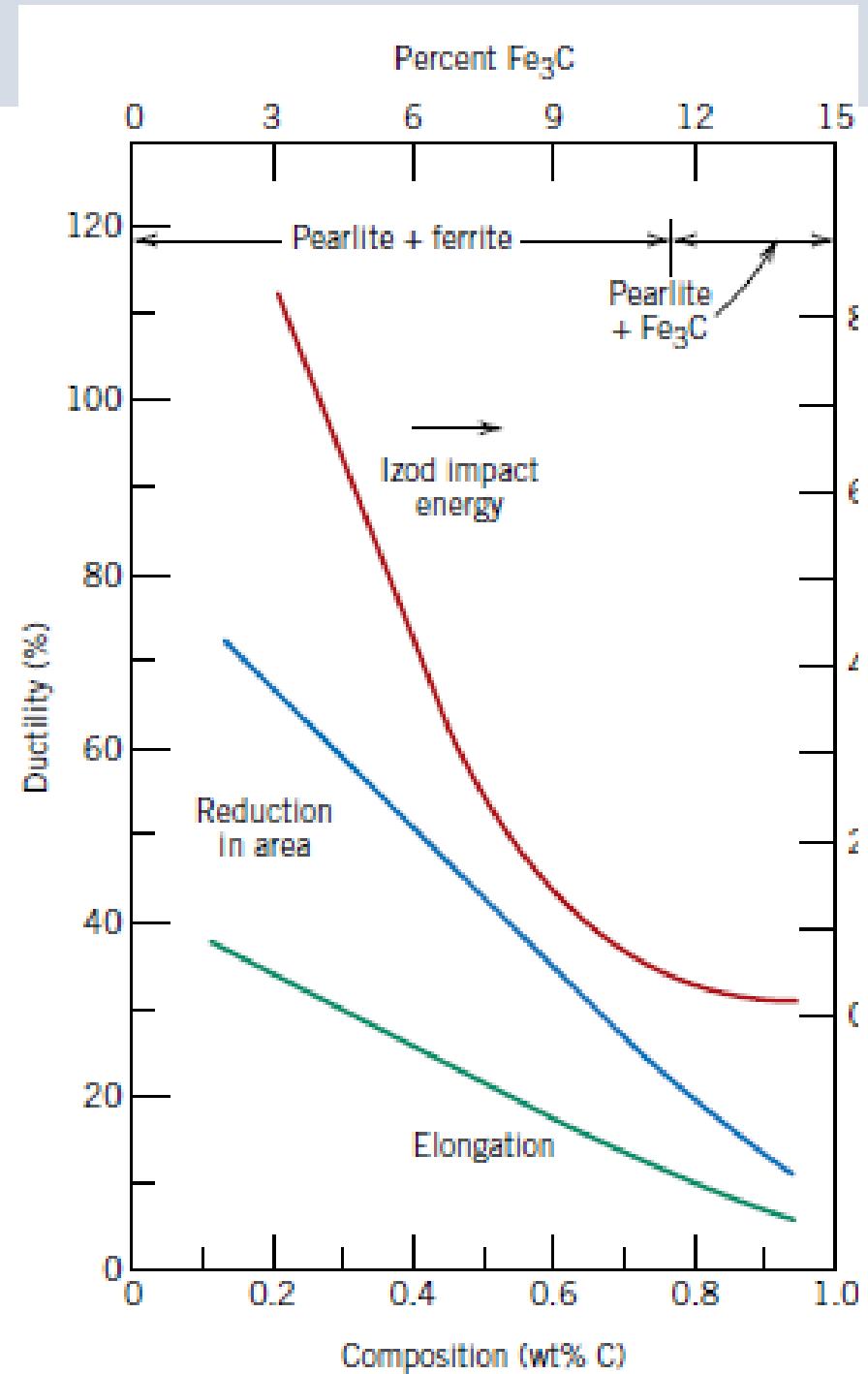
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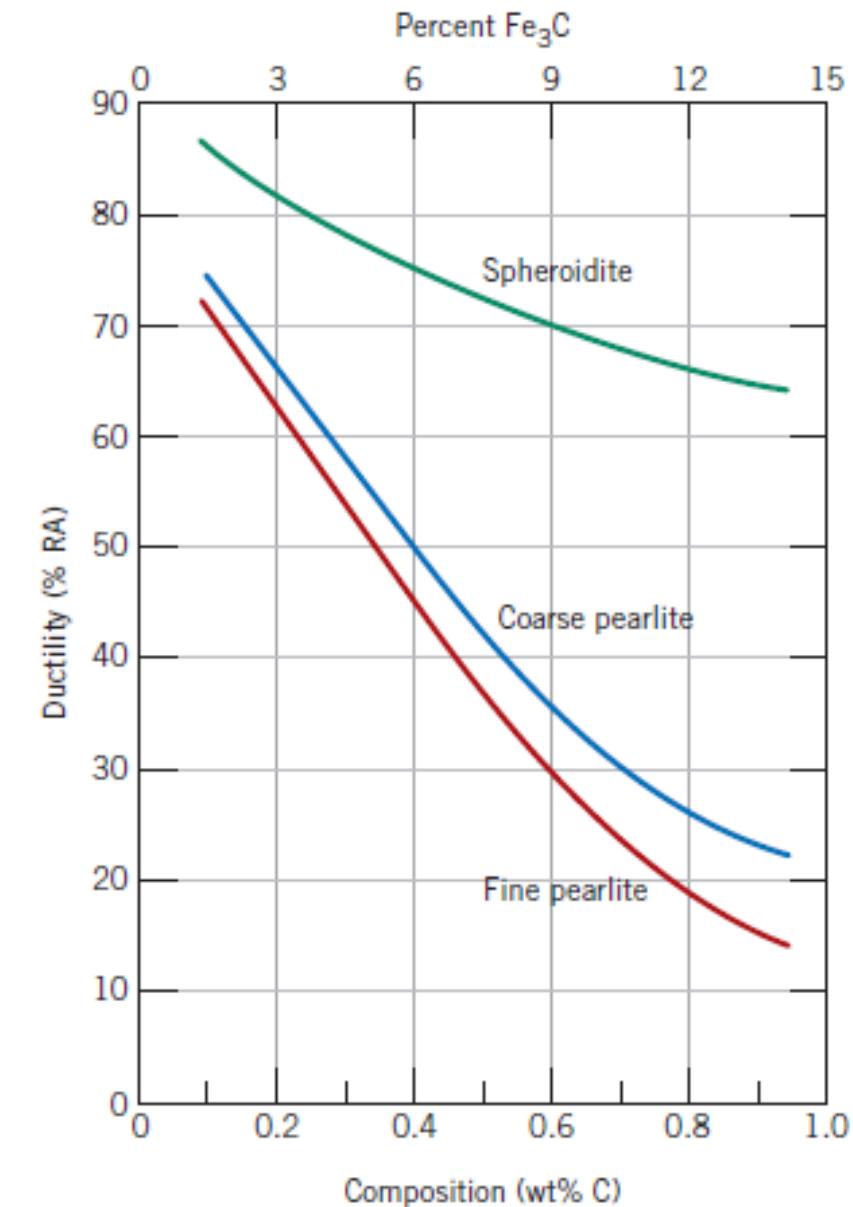
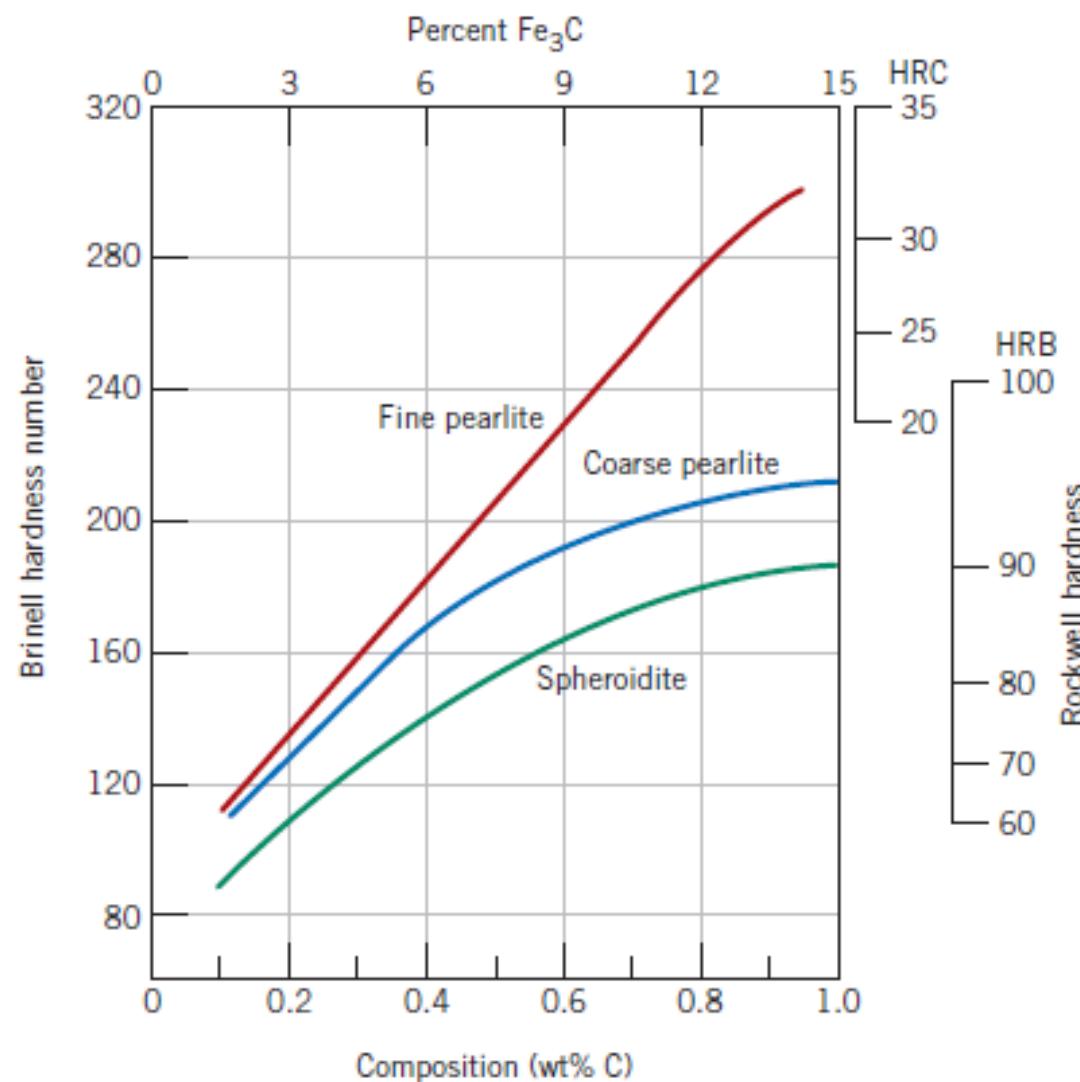
Pearlite:

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Mechanical Behaviour of Iron–Carbon Alloys

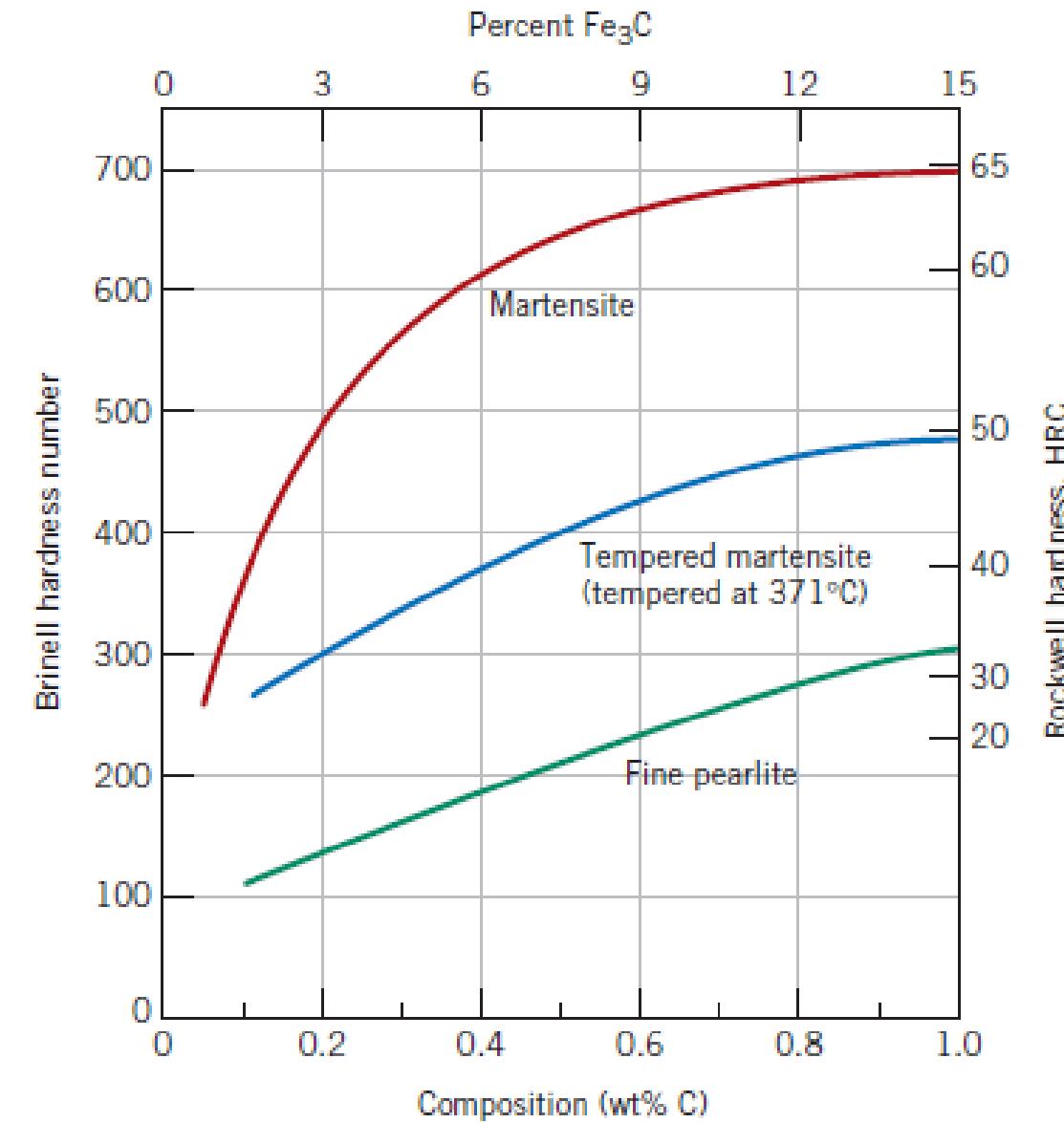
Fine Pearlite Vs Coarse Pearlite Vs Spheroidite



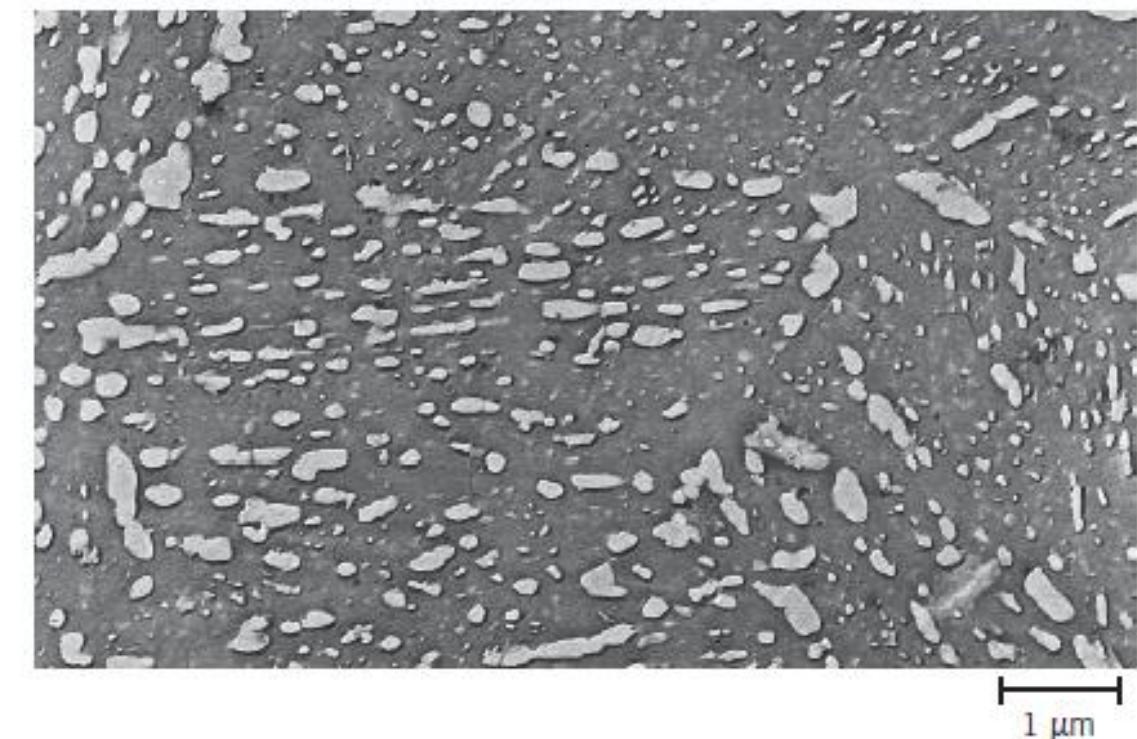
Mechanical Behaviour of Iron–Carbon Alloys

Tempered Martensite

heat treated of **martensite** between 250°C and 650°C

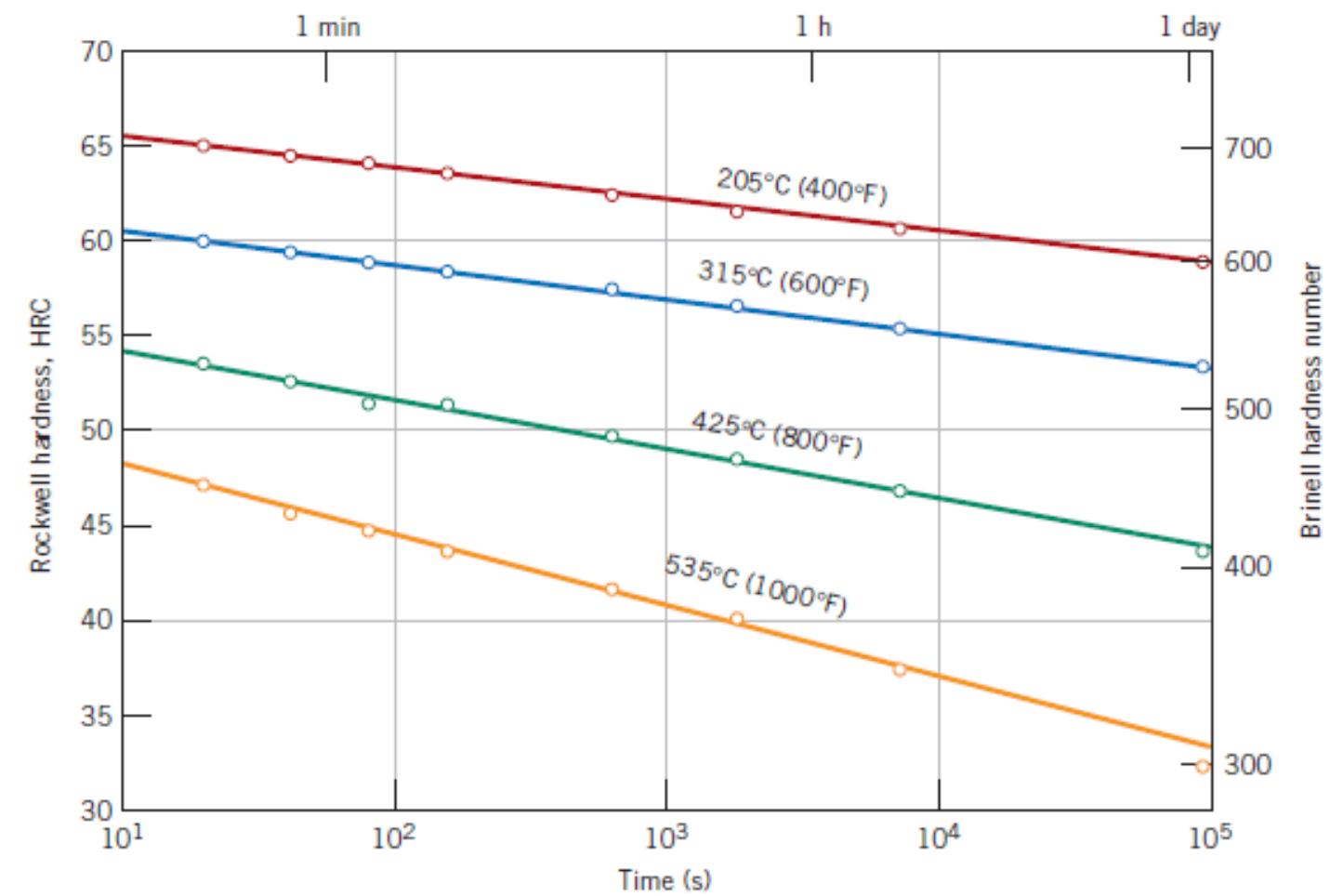
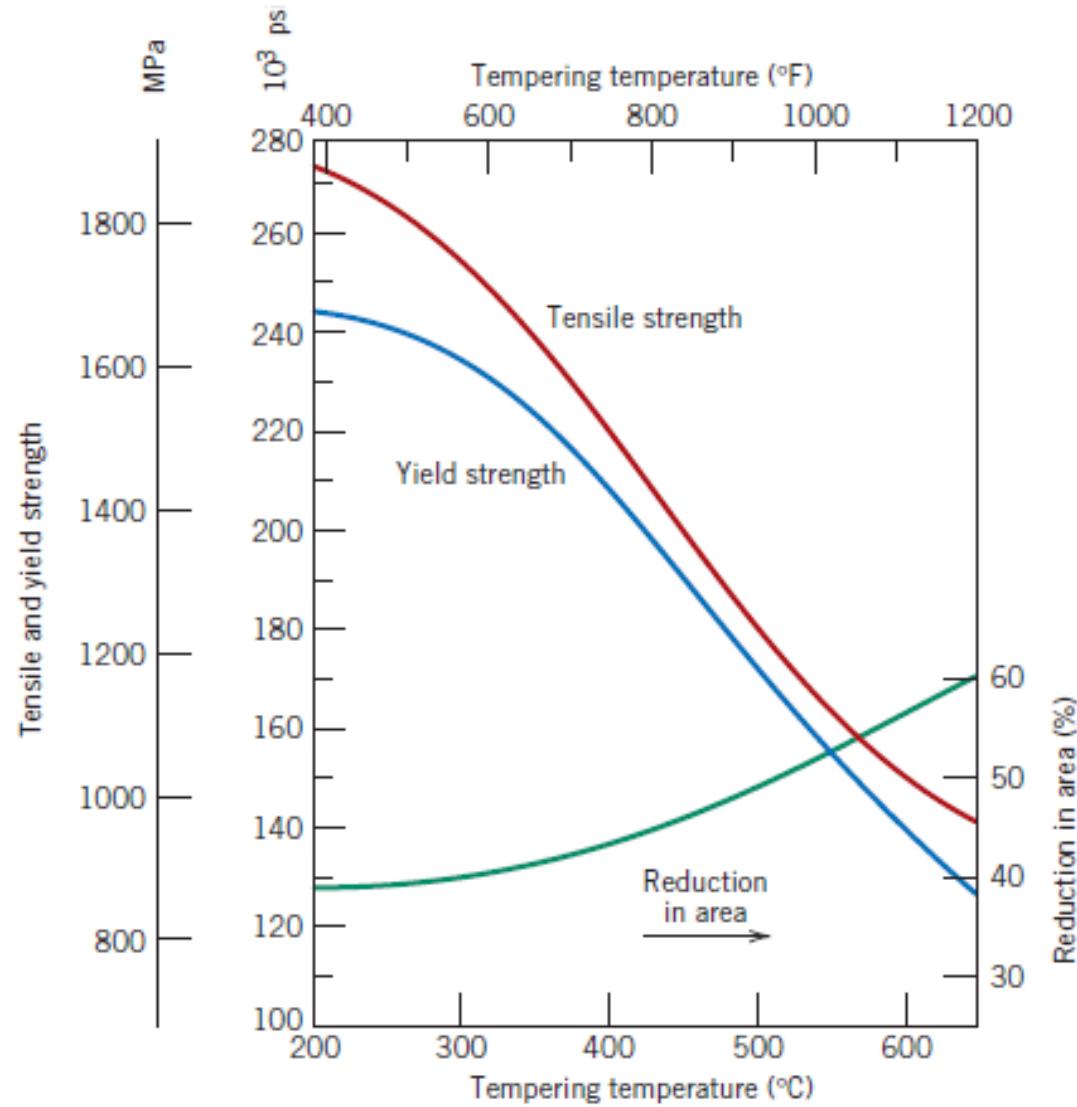


martensite (BCT, single phase) → tempered martensite ($\alpha + \text{Fe}_3\text{C}$ phases)



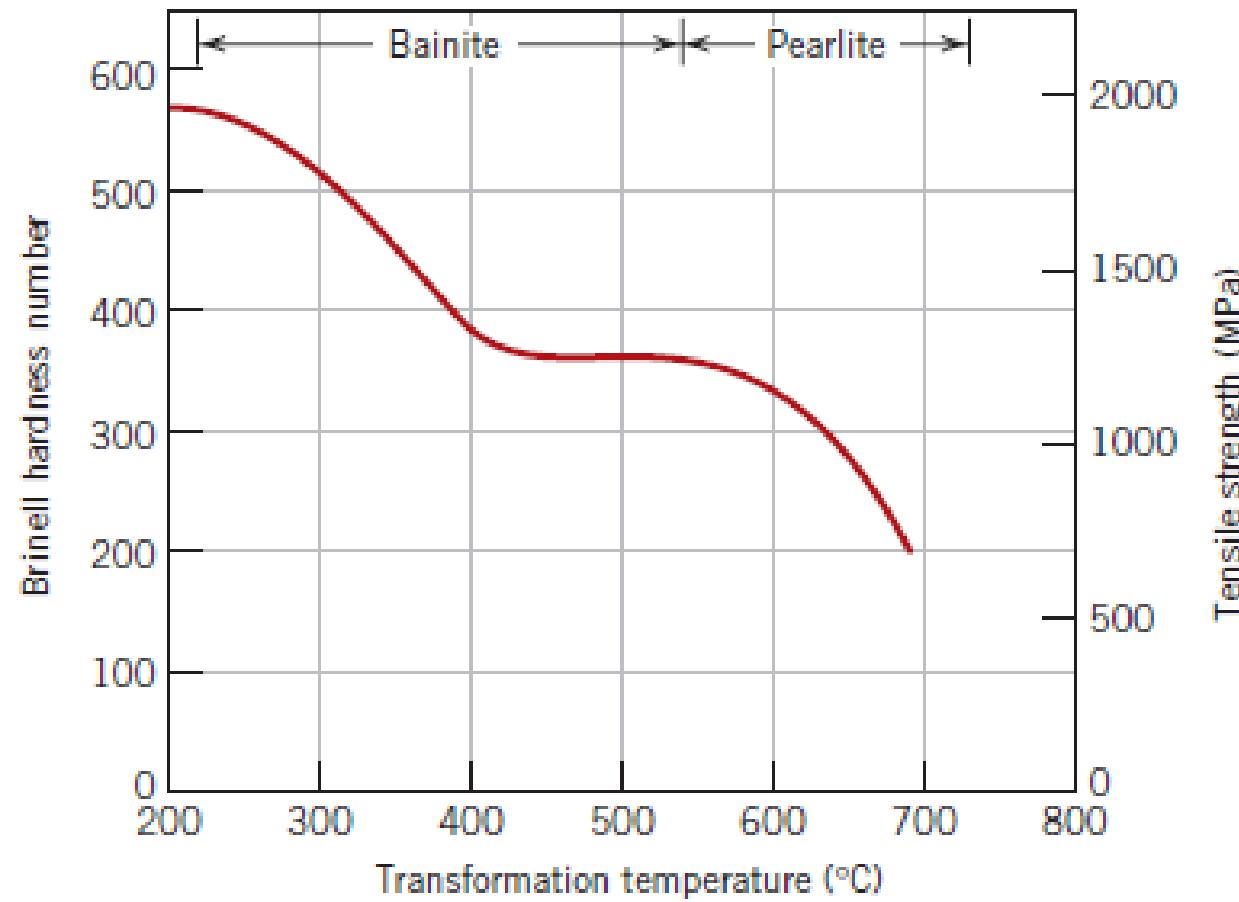
Mechanical Behaviour of Iron–Carbon Alloys

Tempered Martensite

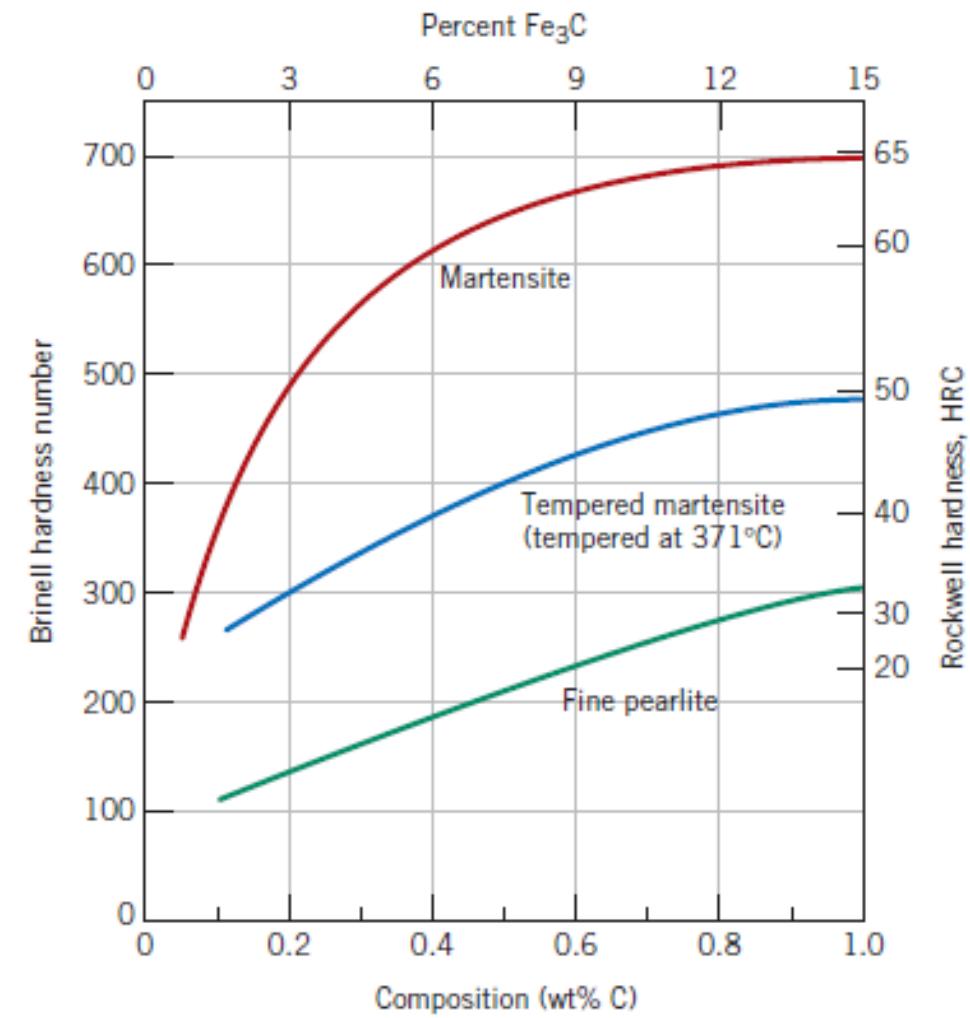


Mechanical Behaviour of Iron–Carbon Alloys

Bainite

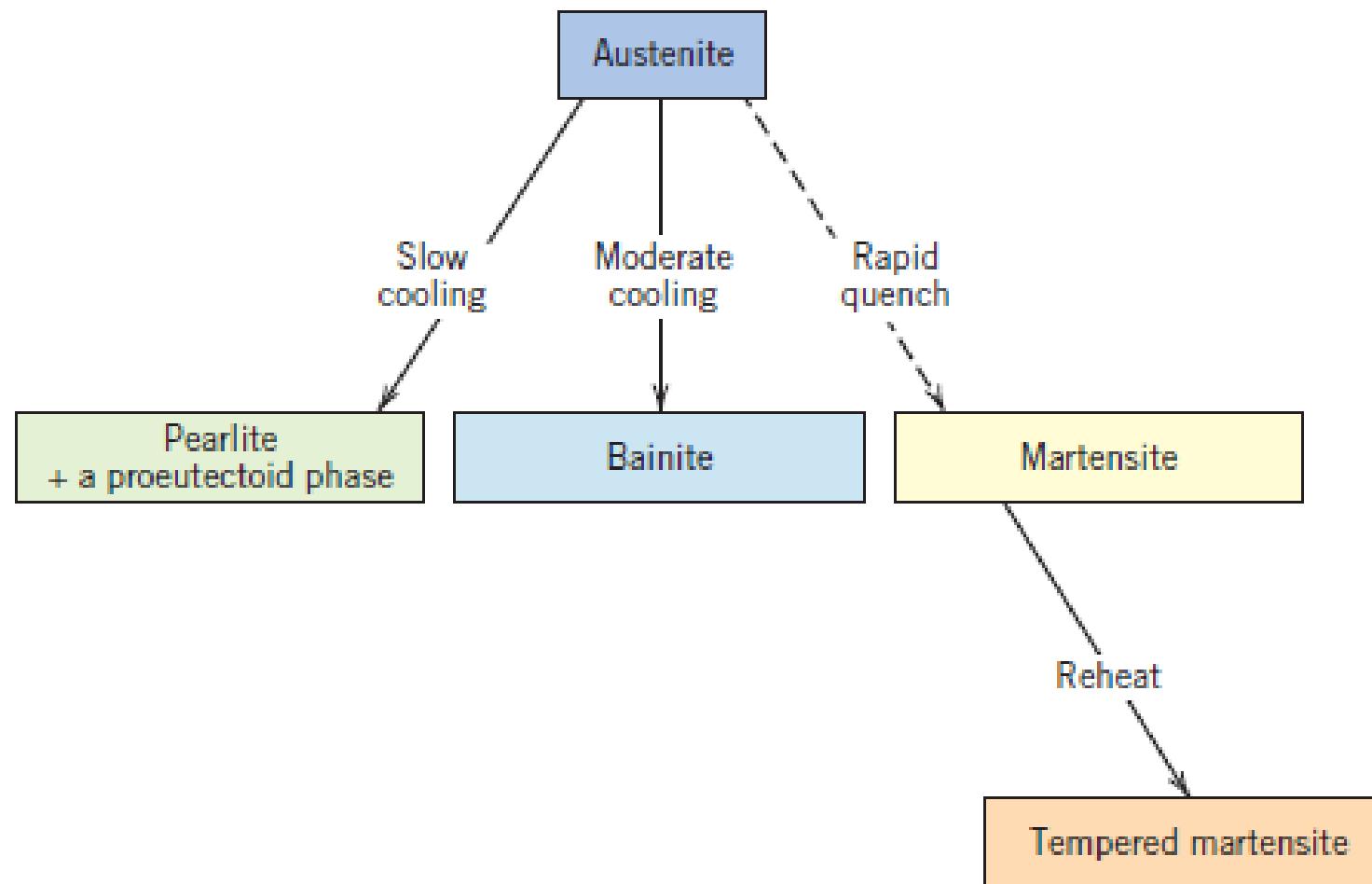


Martensite and Tempered Martensite



Review and Summary

Possible Phase Transformations



Review and Summary

Microstructures and their properties

<i>Microconstituent</i>	<i>Phases Present</i>	<i>Arrangement of Phases</i>	<i>Mechanical Properties (Relative)</i>
Spheroidite	α Ferrite + Fe ₃ C	Relatively small Fe ₃ C sphere-like particles in an α -ferrite matrix	Soft and ductile
Coarse pearlite	α Ferrite + Fe ₃ C	Alternating layers of α ferrite and Fe ₃ C that are relatively thick	Harder and stronger than spheroidite, but not as ductile as spheroidite
Fine pearlite	α Ferrite + Fe ₃ C	Alternating layers of α ferrite and Fe ₃ C that are relatively thin	Harder and stronger than coarse pearlite, but not as ductile as coarse pearlite
Bainite	α Ferrite + Fe ₃ C	Very fine and elongated particles of Fe ₃ C in an α -ferrite matrix	Hardness and strength greater than fine pearlite; hardness less than martensite; ductility greater than martensite
Tempered martensite	α Ferrite + Fe ₃ C	Very small Fe ₃ C sphere-like particles in an α -ferrite matrix	Strong; not as hard as martensite, but much more ductile than martensite
Martensite	Body-centered tetragonal, single phase	Needle-shaped grains	Very hard and very brittle

Microstructures and their properties

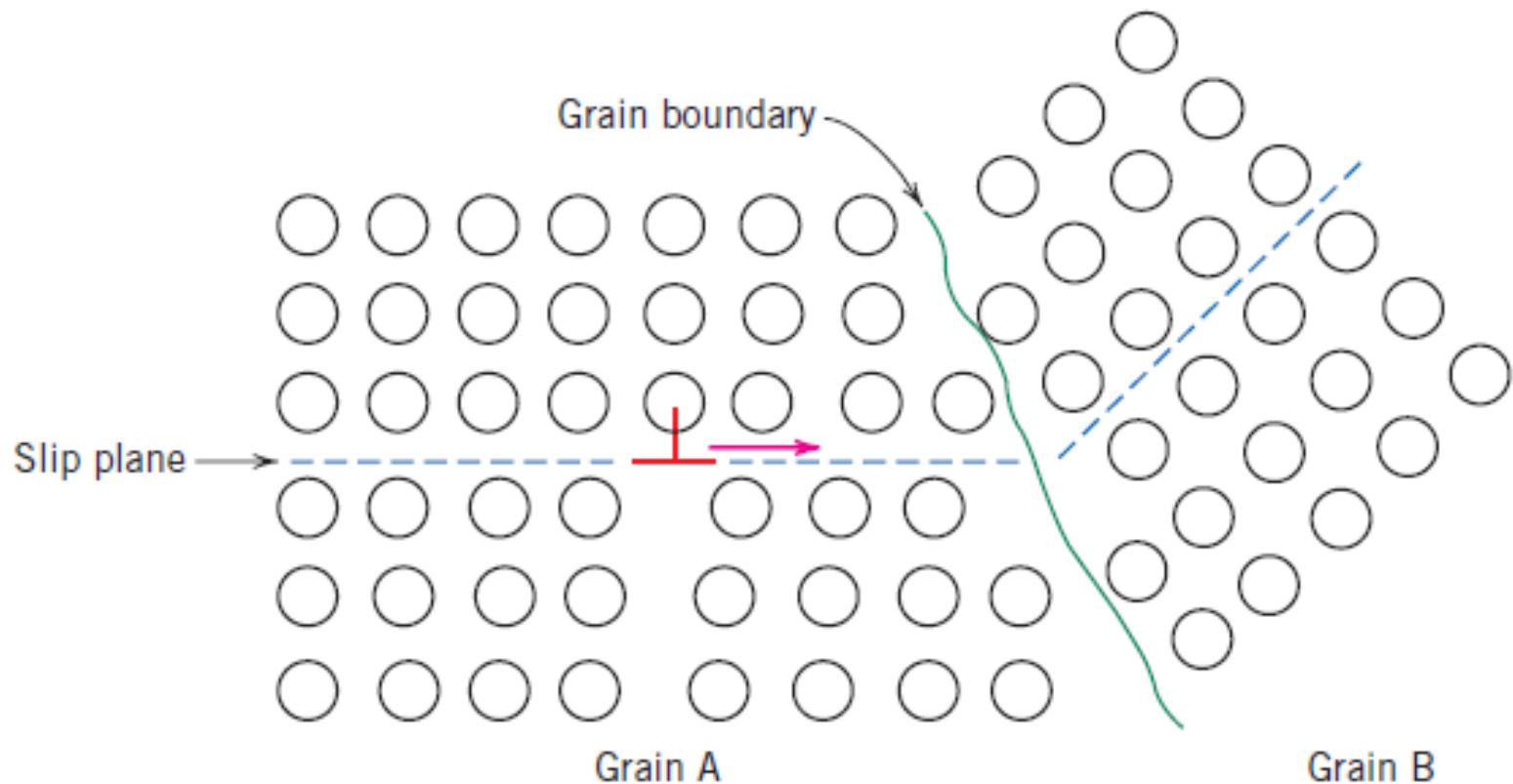
Strengthening Mechanisms in Metals

“Restricting or hindering dislocation motion renders a material harder and stronger”

- Grain size reduction
- Solid – Solution Strengthening
- Strain Hardening

Strengthening Mechanisms in Metals – Grain size reduction

- Grain boundary is a discontinuity in atomic order.
- As a result grain boundary acts as an obstacle to dislocation motion.
- The dislocations tend to pile up at the high-angle grain boundaries
- Smaller the grains are in a polycrystalline material, higher the grain boundary area. Hence, a fine-grained material is harder and stronger.

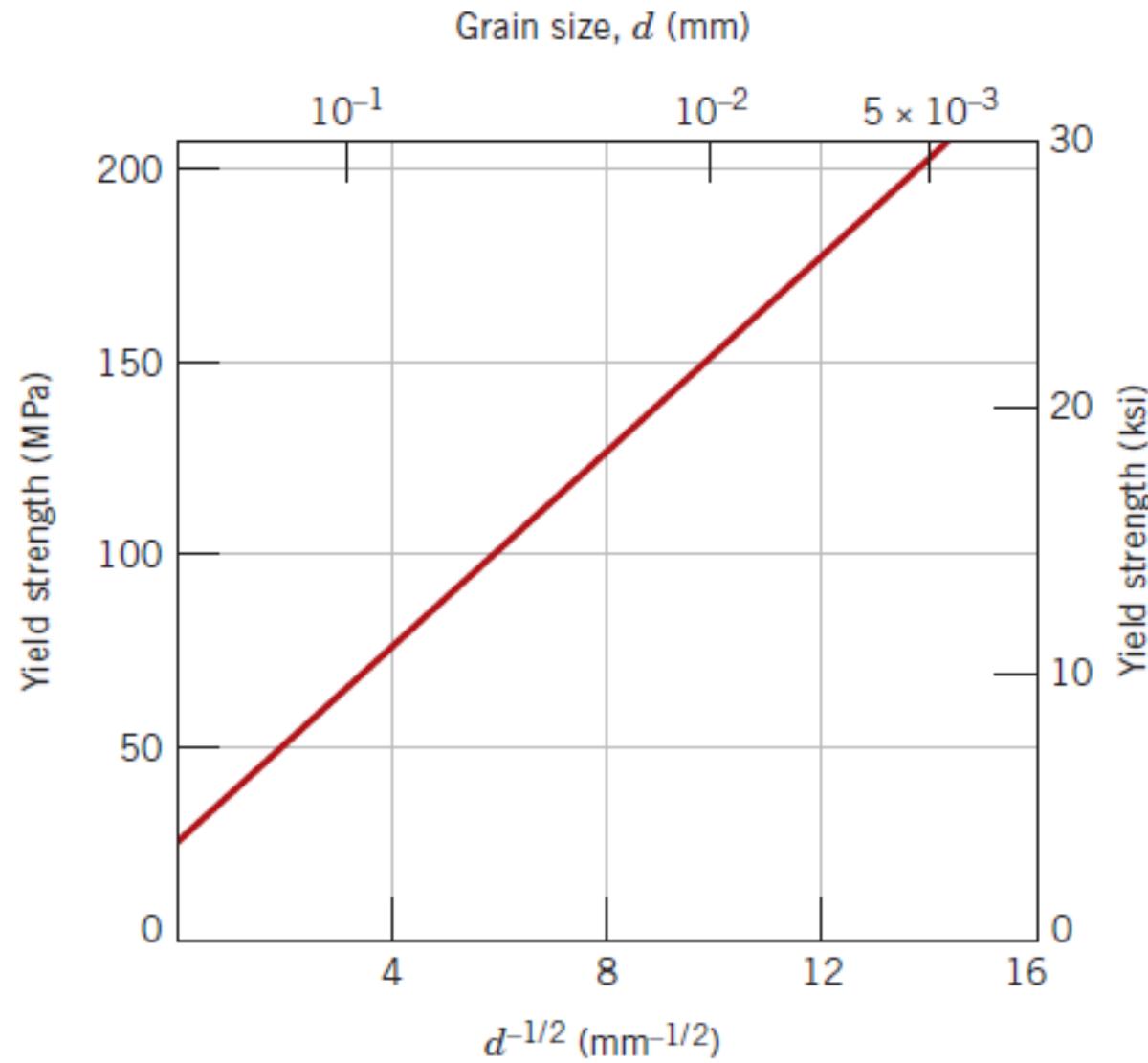


Strengthening Mechanisms in Metals – Grain size reduction

$$\sigma_y = \sigma_0 + k_y d^{-1/2}$$

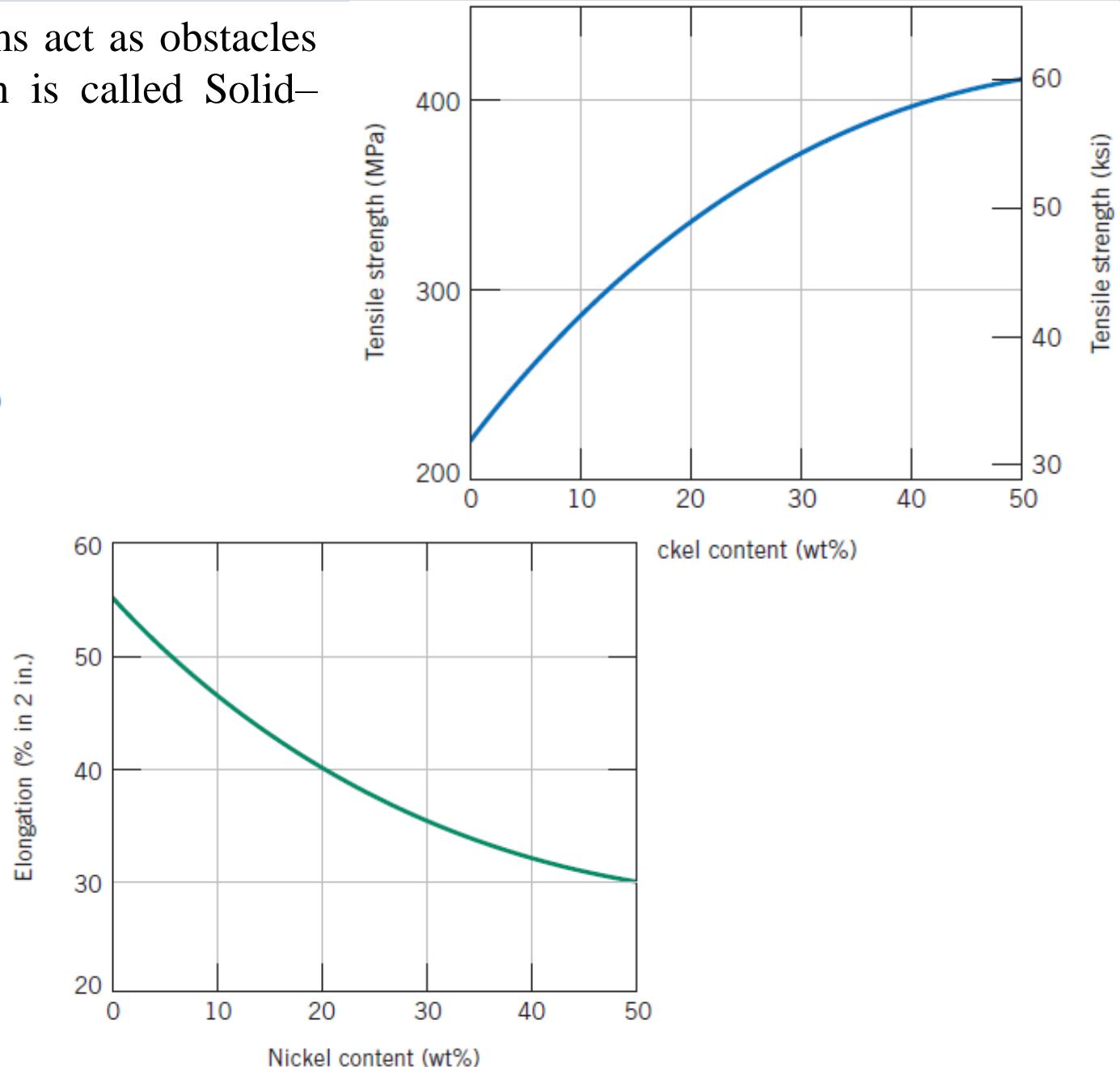
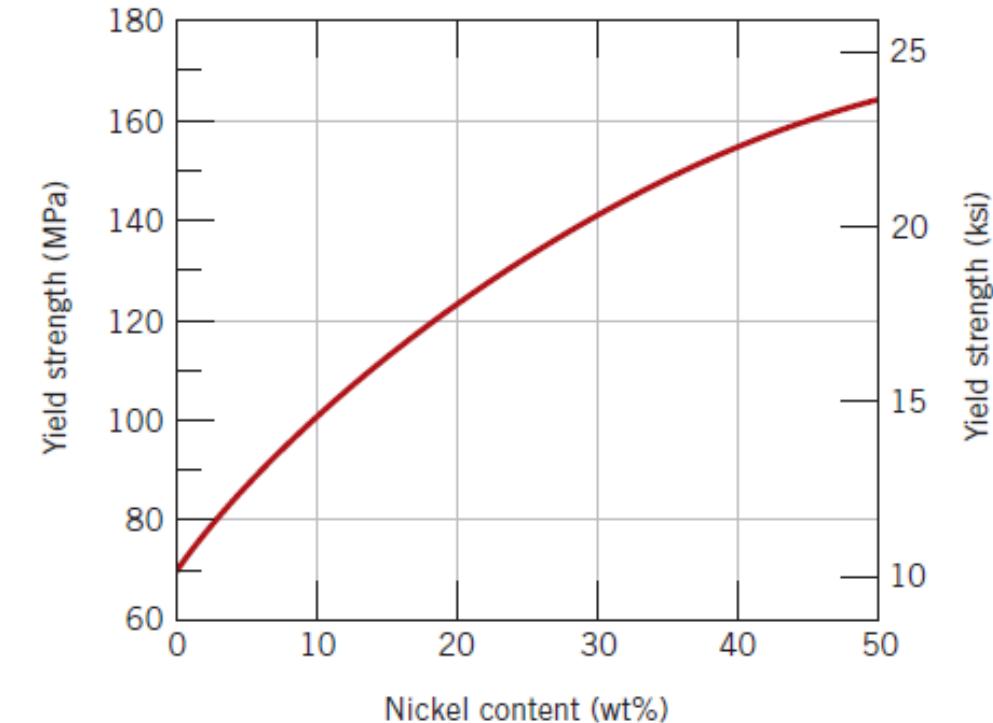
Yield Strength Variation With Grain Size: **Hall – Petch relation**

- d is the average grain size.
- σ_0 and d are constants for a particular material.
- Small angle grain boundaries are not as effective in hindering the slipping process.
- For more complex alloys, phase boundaries act as obstacles to dislocation motion.

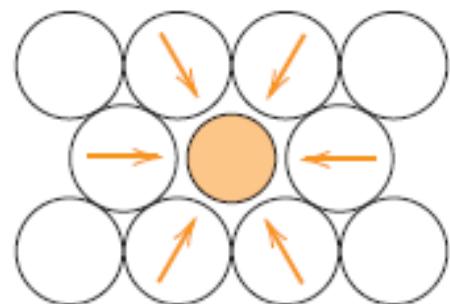


Strengthening Mechanisms in Metals – Solid Solution Strengthening

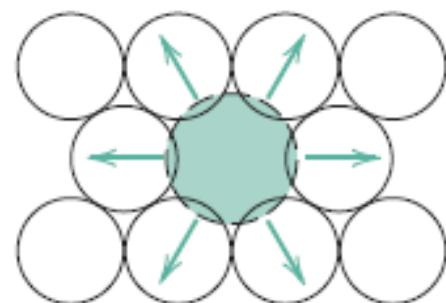
- Substitutional or interstitial impurity atoms act as obstacles to dislocation motion. This phenomenon is called Solid-Solution strengthening.



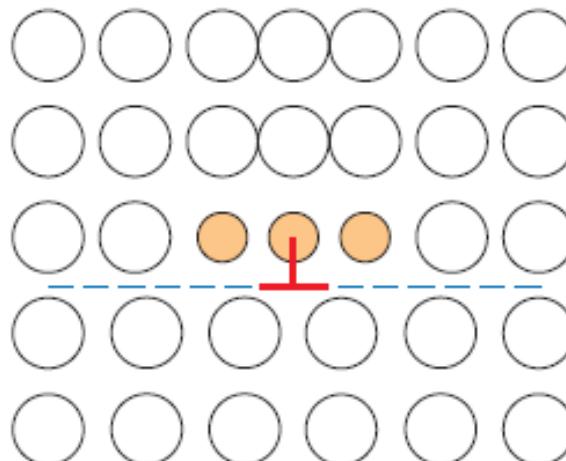
Strengthening Mechanisms in Metals – Solid Solution Strengthening



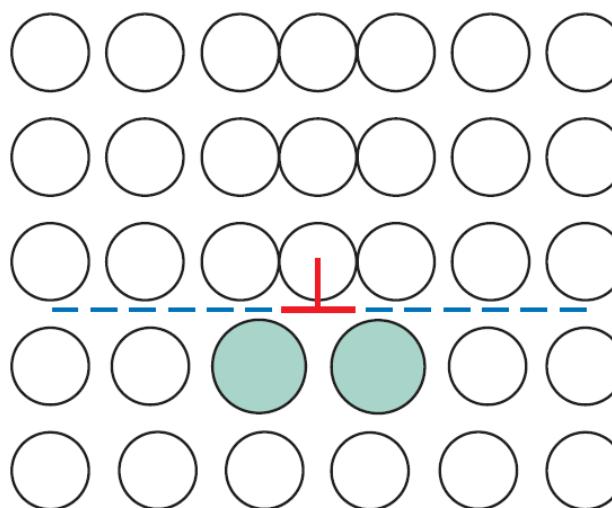
Tensile strains induced in the case where, a smaller atom “substitutes” a parent atom.



Compressive strains induced in the case where, a bigger atom “substitutes” a parent atom.



Tensile strains due to smaller substitutional atoms interact with compressive strains of a dislocation, restricting further motion of the dislocation.

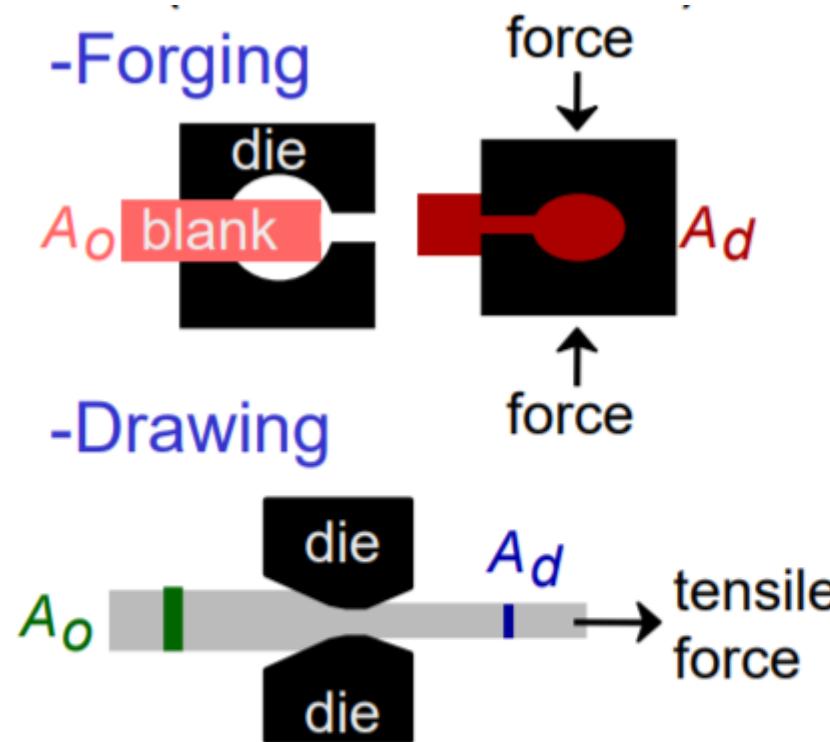


Compressive strains due to bigger substitutional atoms interact with tensile strains of a dislocation, restricting further motion of the dislocation.

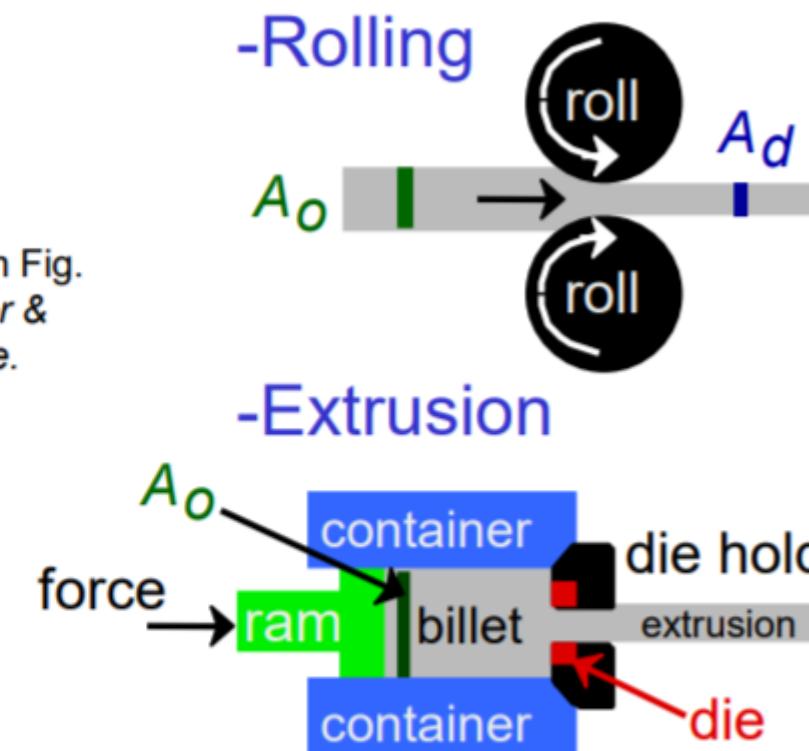
Strengthening Mechanisms in Metals – Strain Hardening

Also called “Work Hardening” or “Cold Working”.

Deformation at room temperature



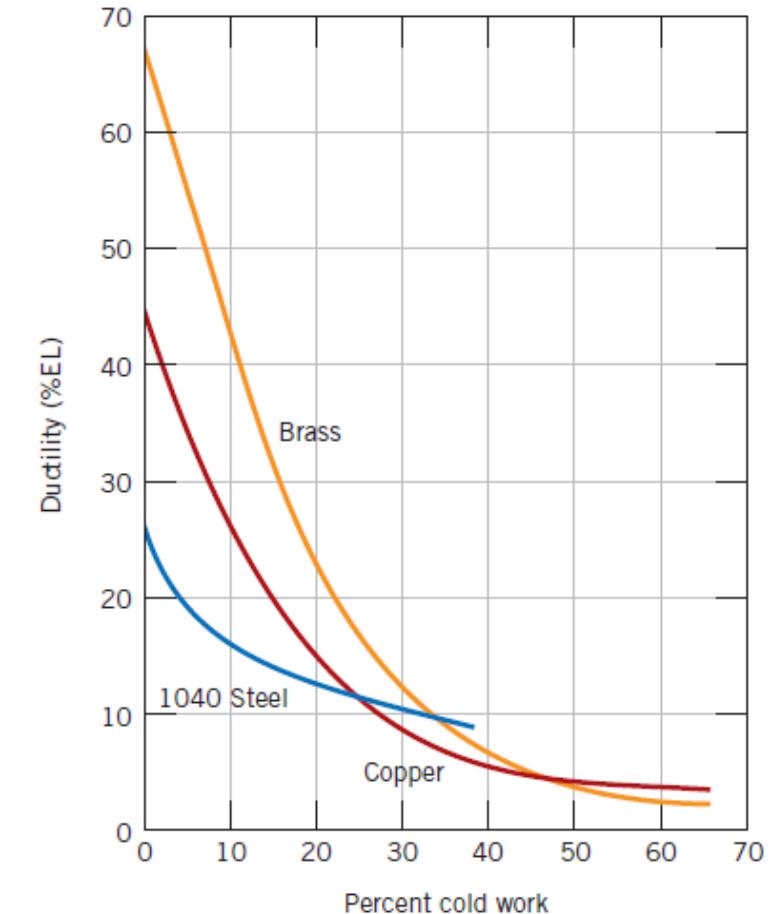
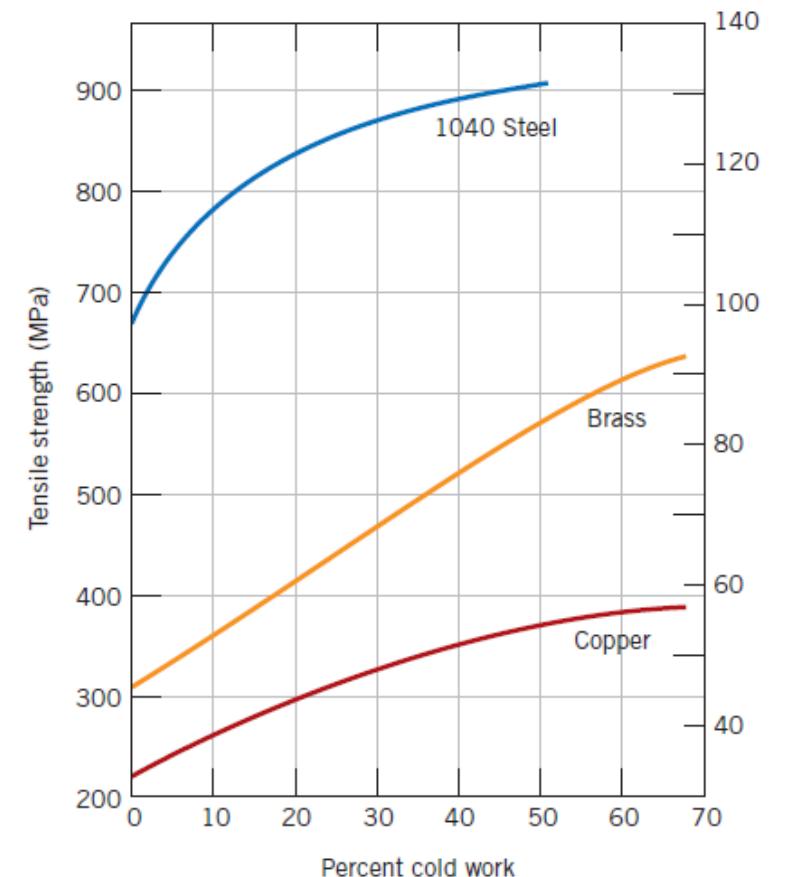
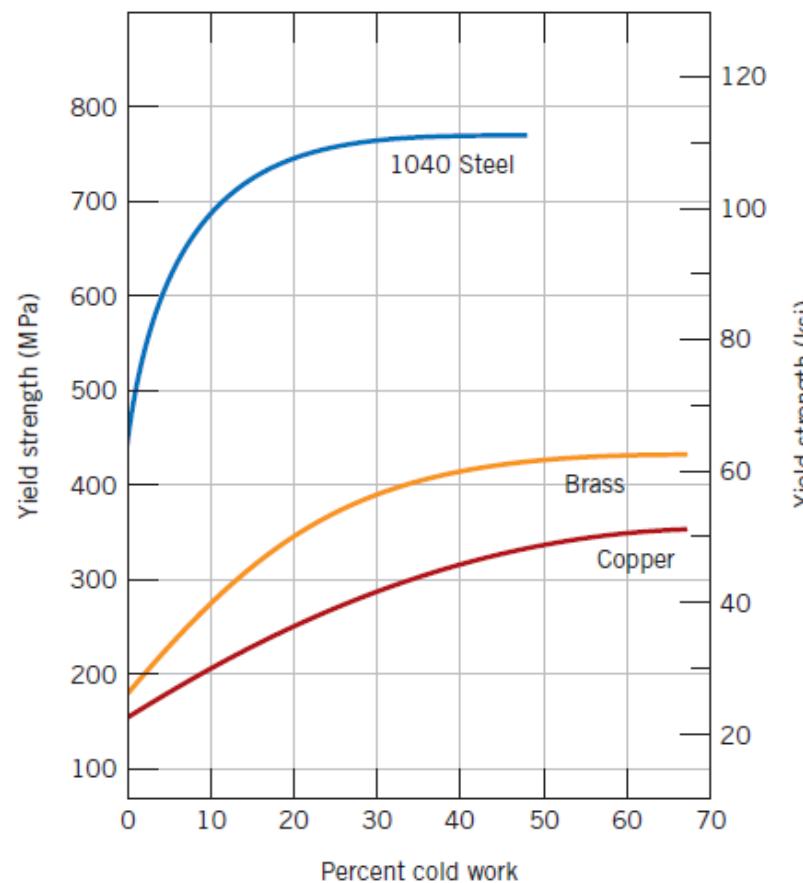
Adapted from Fig.
11.8, Callister &
Rethwisch 8e.



$$\% \text{ CW} = \frac{A_o - A_d}{A_o} \times 100$$

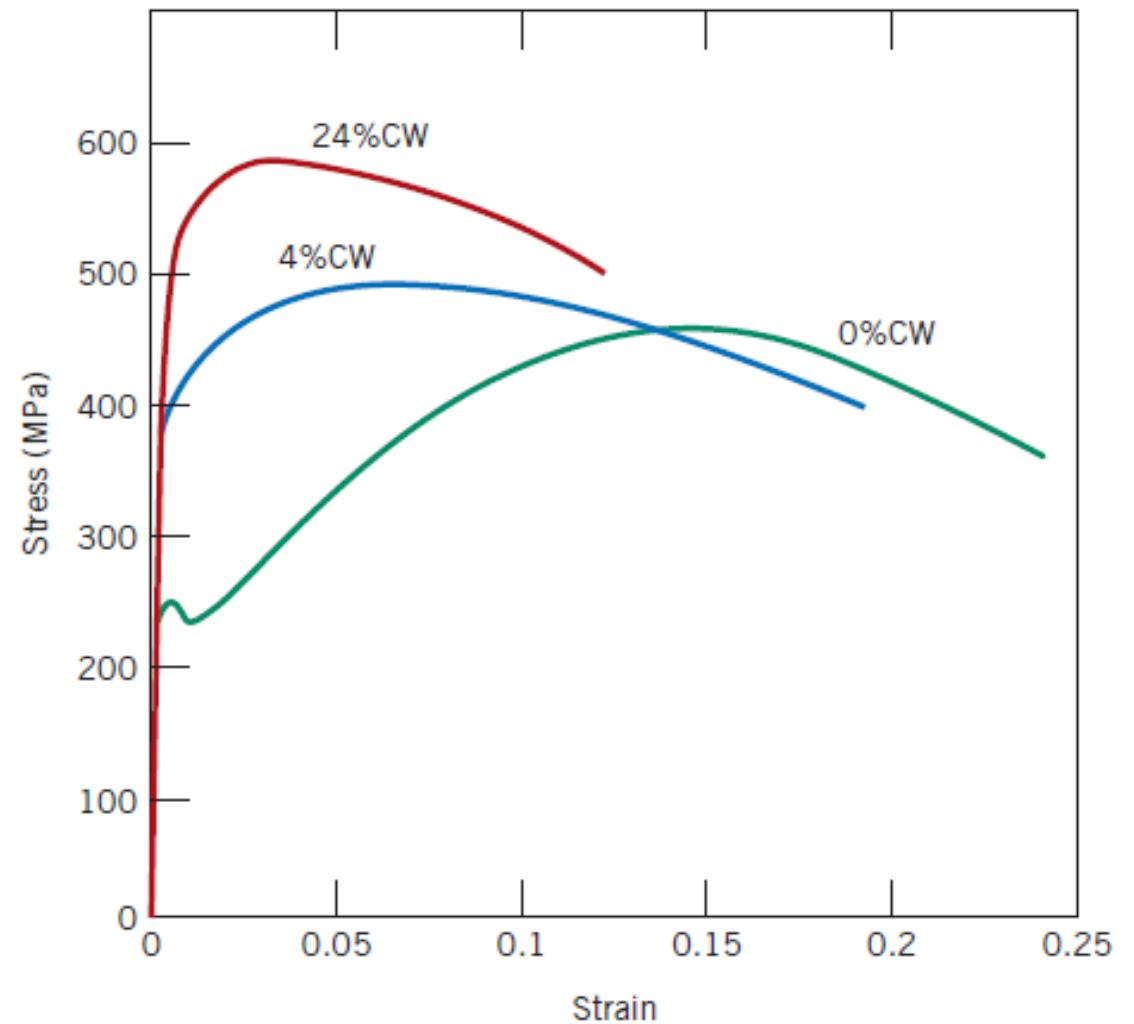
Strengthening Mechanisms in Metals – Strain Hardening

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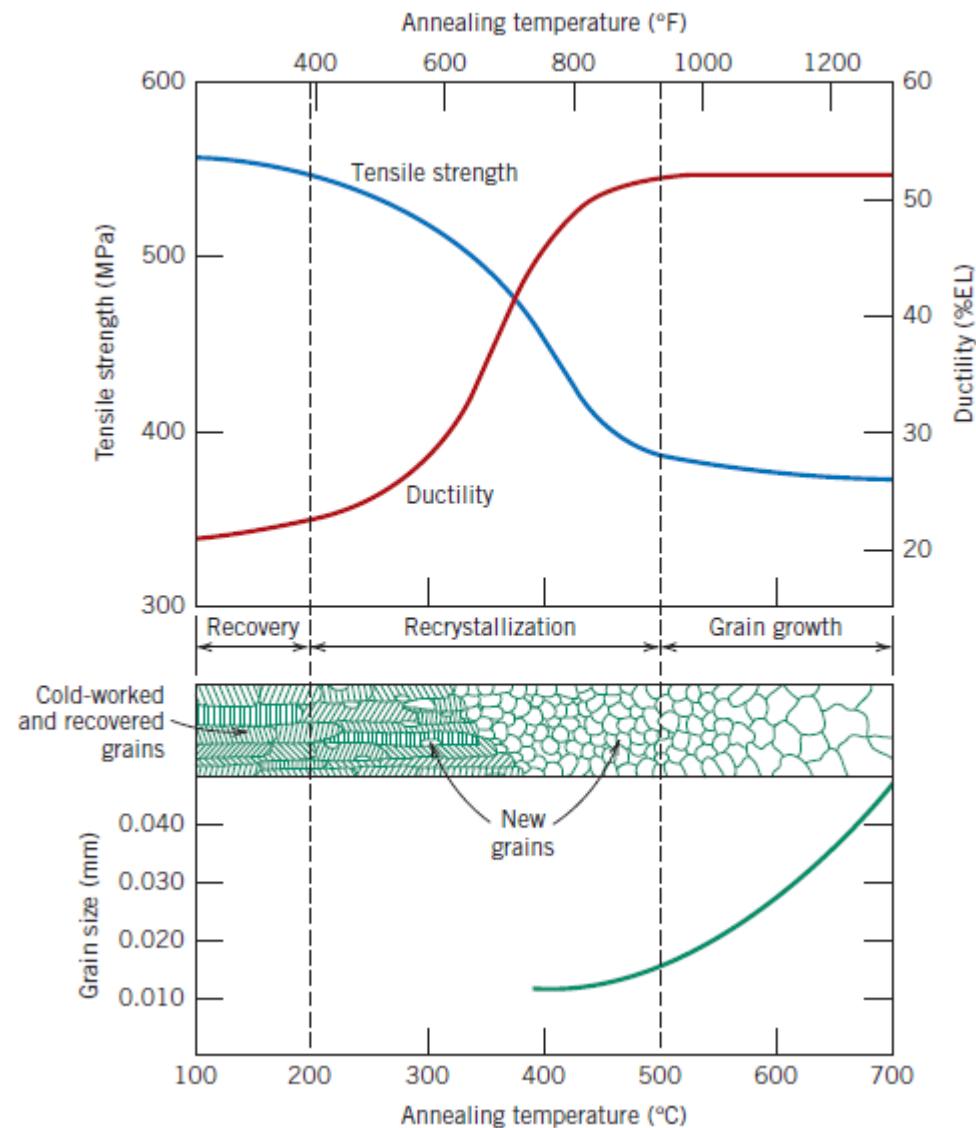


Strengthening Mechanisms in Metals – Strain Hardening

Cold working in low carbon steel

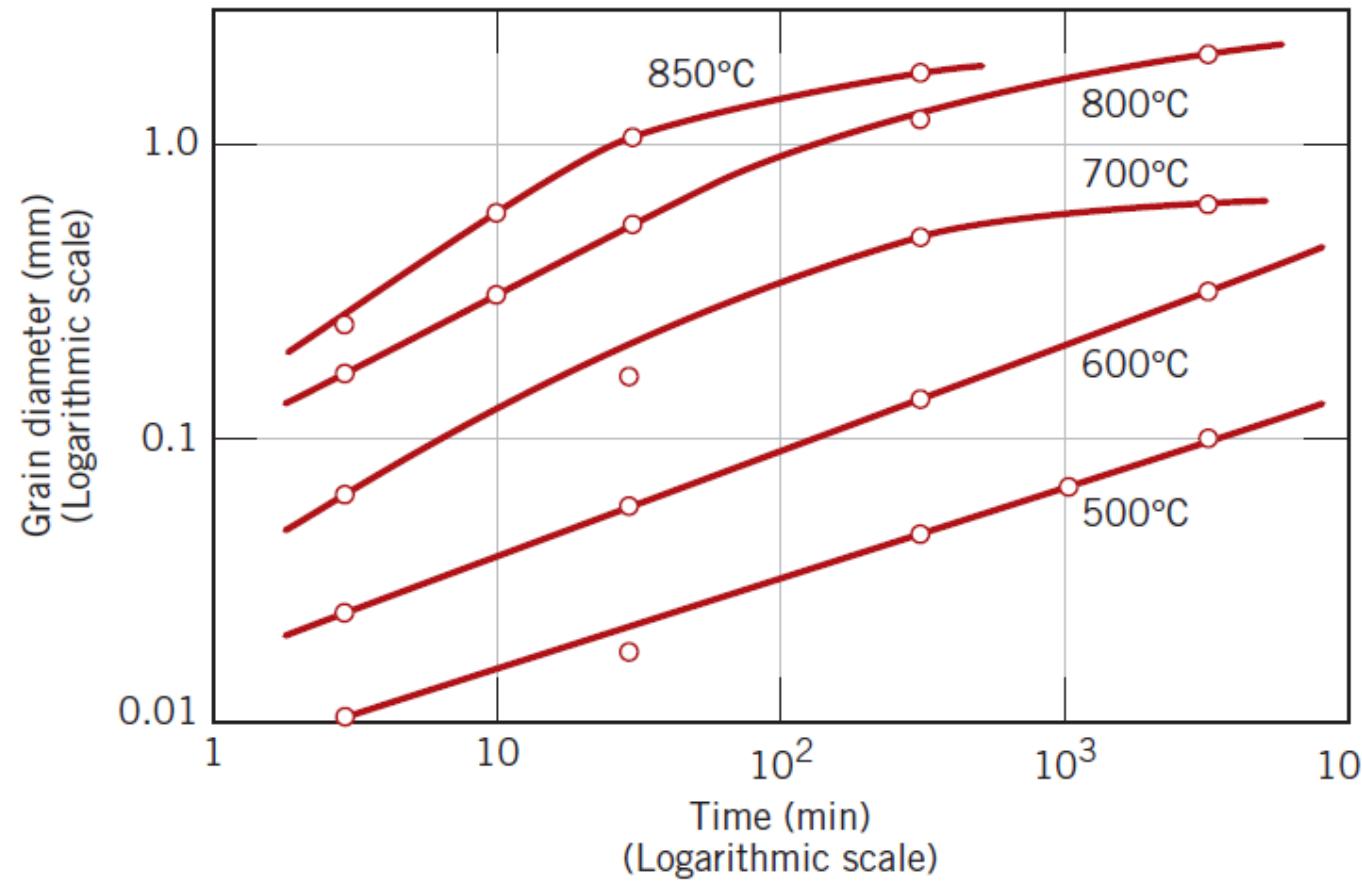
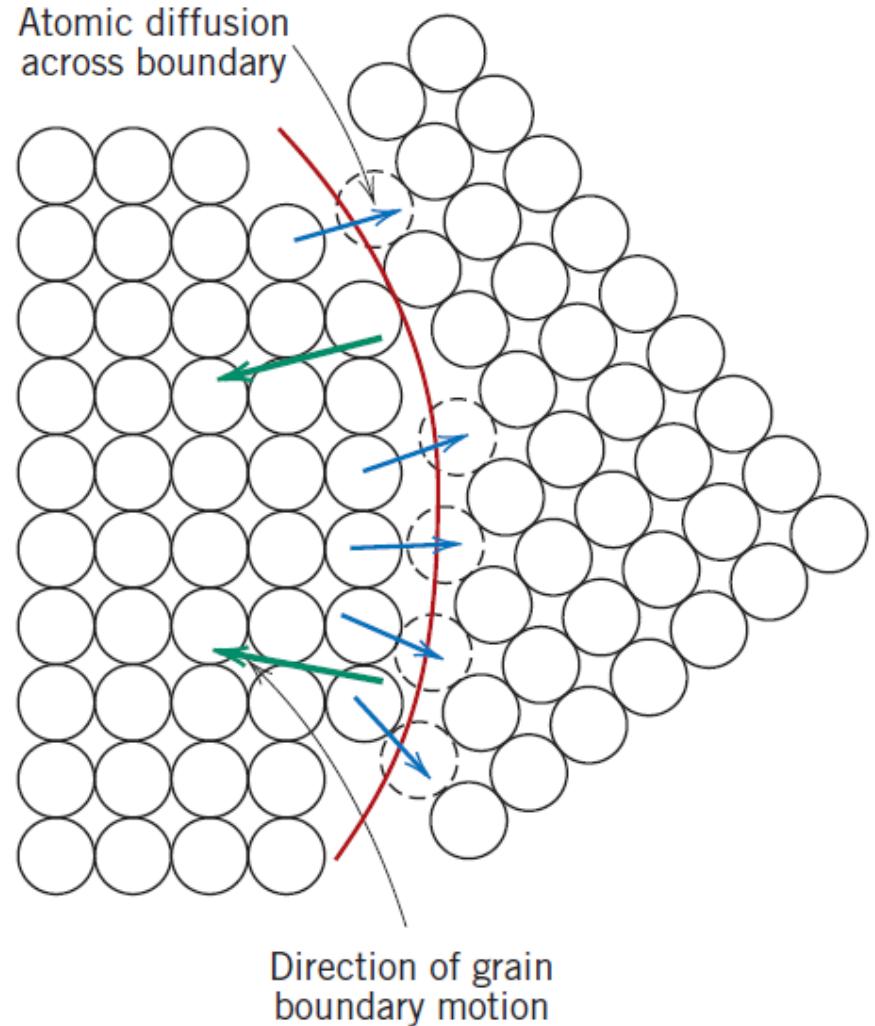


Effect of Heat Treating After Cold Working of Metals



The influence of annealing temperature (annealing time of 1 h)
The tensile strength and ductility of a brass alloy.

Grain growth



Grain growth & dependence of grain size on time

For many polycrystalline materials, the grain diameter d varies with time t according to the relationship

$$d^n - d_0^n = Kt \quad (7.9)$$

where d_0 is the initial grain diameter at $t = 0$, and K and n are time-independent constants; the value of n is generally equal to or greater than 2.

Computation of Grain Size after Heat Treatment

When a hypothetical metal having a grain diameter of 8.2×10^{-3} mm is heated to 500°C for 12.5 min, the grain diameter increases to 2.7×10^{-2} mm. Compute the grain diameter when a specimen of the original material is heated at 500°C for 100 min. Assume the grain diameter exponent n has a value of 2.

GIBBS Phase Rule

$$P + F = C + N$$

P is the number of phases present

F is the externally controlled variables (e.g., temperature, pressure, composition)

C is the number of components in the system.

N is number of noncompositional variables (e.g., temperature and pressure).

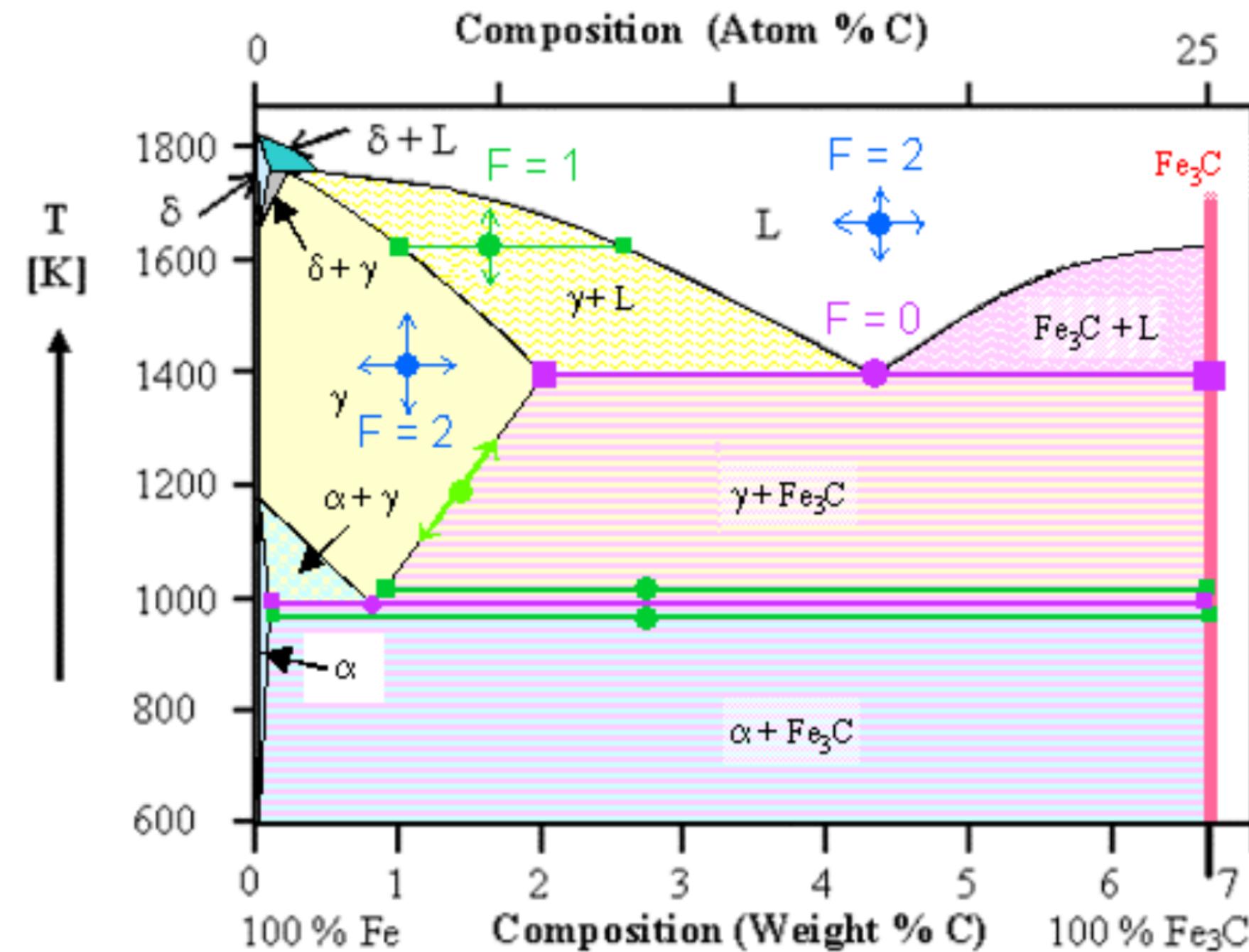
Because pressure is constant (1 atm)

$N = 1$ (Temperature is the only noncompositional variable)

Number of components C is 2

$$P + F = 2 + 1 = 3$$

$$F = 3 - P$$



For binary systems, when three phases are present, there are no degrees of freedom because

$$\begin{aligned}F &= 3 - P \\&= 3 - 3 = 0\end{aligned}$$

Concept Question 1 For a ternary system, three components are present; temperature is also a variable. What is the maximum number of phases that may be present for a ternary system, assuming that pressure is held constant?

Answer: For a ternary system ($C = 3$) at constant pressure ($N = 1$), Gibbs phase rule,

$$P + F = C + N = 3 + 1 = 4$$

Or,

$$P = 4 - F$$

Thus, when $F = 0$, P will have its maximum value of 4, which means that the maximum number of phases present for this situation is 4.