THE UNIVERSITY OF ZAMBIA
SCHOOL OF ENGINEERING
DEPARTMENT OF MECHANICAL ENGINEERING

MEC 2309 – PROPERTIES OF ENGINEERING MATERIALS I

LECTURE 9

THE IRON-CARBON SYSTEM

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INTRODUCTION

- Of all binary alloy systems, the one that is possibly the most important is that for iron and carbon.
- Both steels and cast irons, primary structural materials in every technologically advanced culture, are essentially **iron–carbon alloys**.
- This lecture is devoted to a study of the phase diagram for this system and the development of several of the possible microstructures.

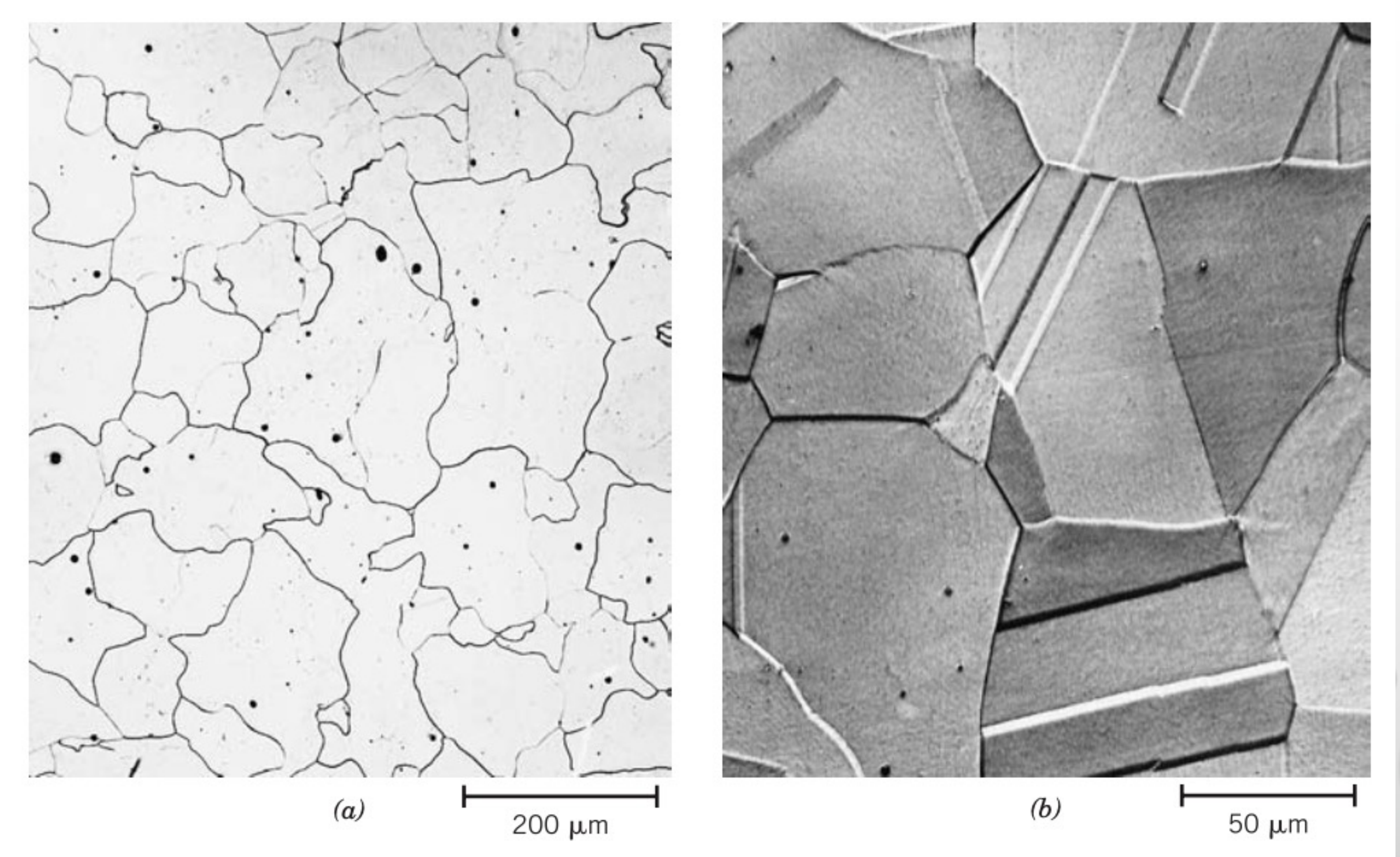
INTRODUCTION

- The Iron-Carbon phase diagram gives the various grades of steel and irons.
- Steel still the most important construction and engineering material.
- Important to see where various grades of steel belong in the diagram.
- Important to know how to draw it and show its most important features.

ALLOTROPIC FORMS OF PURE IRON

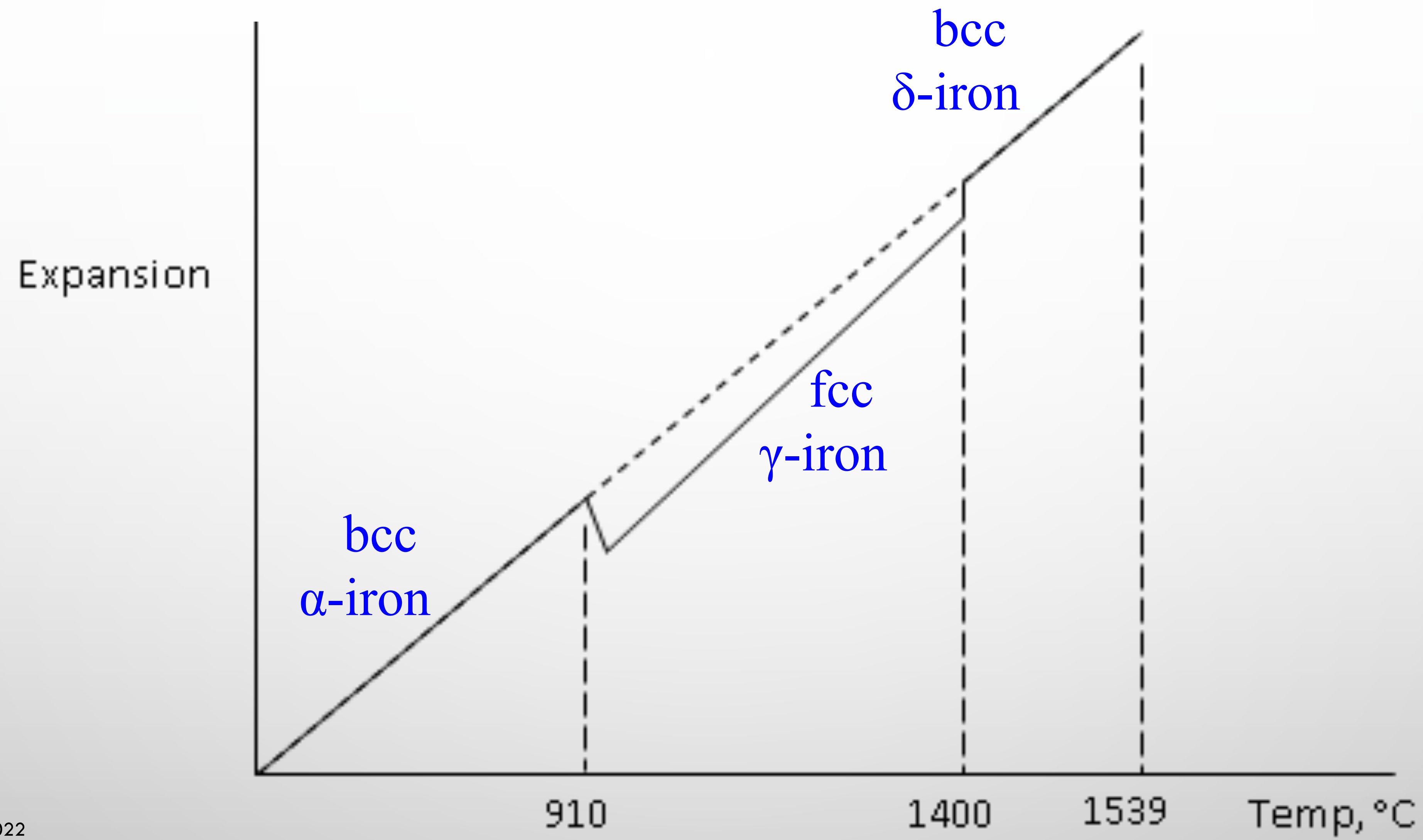
- Pure iron, upon heating, experiences two changes in crystal structure before it melts.
- At room temperature the stable form, called ferrite, or **α-iron** (α-ferrite), , has a BCC crystal structure.
- Ferrite experiences an allotropic (or polymorphic) transformation to FCC austenite, or **γ-iron**, between 910°C - 912°C.
- This austenite persists to 1394°C to 1400°C at which temperature the FCC austenite reverts back to a BCC phase known as **δ-iron** (δ-ferrite), which finally melts at 1538°C or 1539°C .

ALLOTROPIC FORMS OF PURE IRON

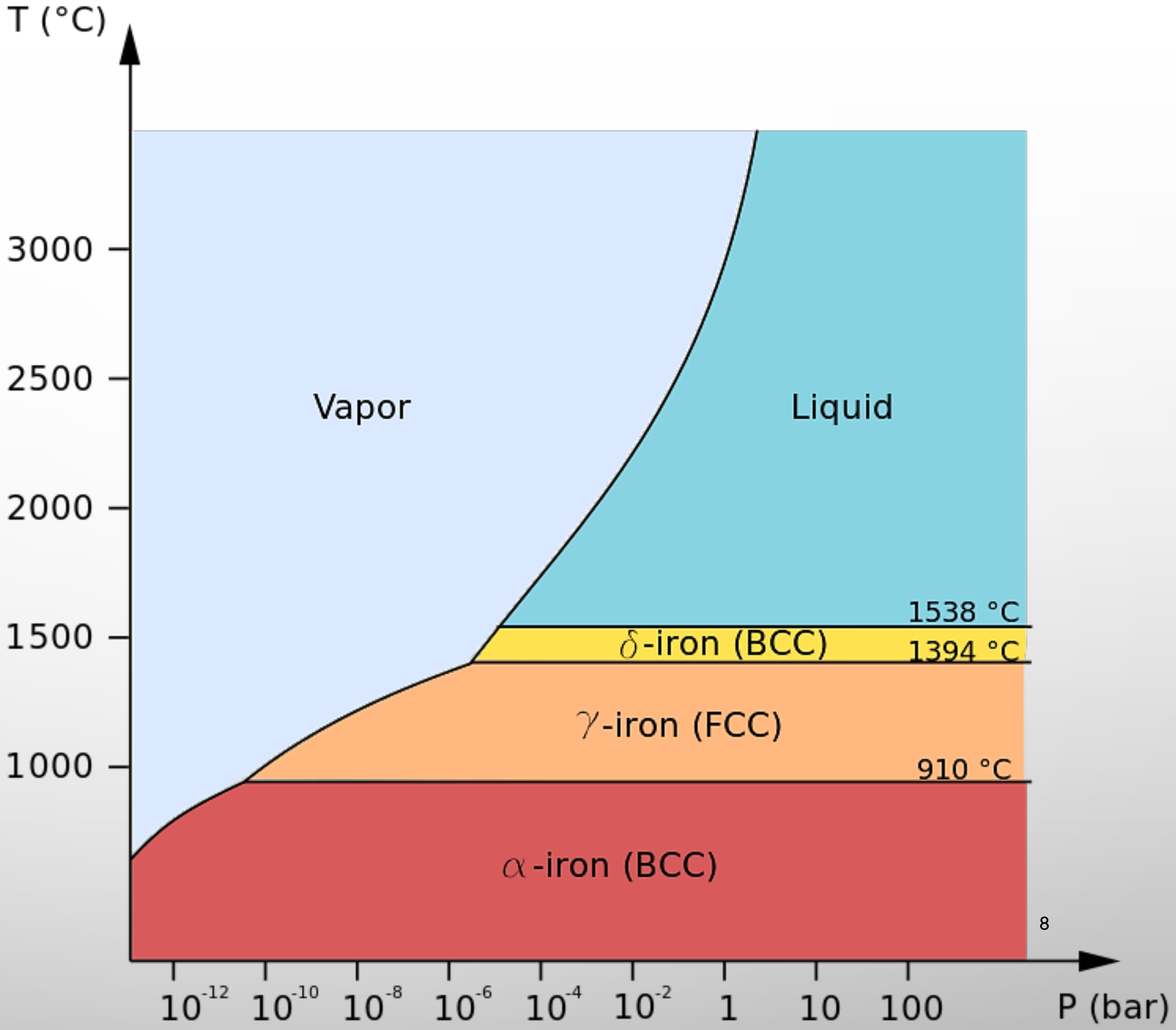


Photomicrographs of (a) α-ferrite (90×) and (b) austenite (325×). (Copyright 1971 by United States Steel Corporation.)

ALLOTROPIC FORMS OF PURE IRON



ALLOTROPIC FORMS OF PURE IRON



ALLOTROPIC FORMS OF PURE IRON

- α-iron loses ferromagnetism at 770^{o}c → the **curie** temperature.
- **γ-iron** is the structure of closest packing while α-iron and δ-iron are not.
- Transitions $\boldsymbol{\alpha} \rightarrow \boldsymbol{\gamma}$ and $\boldsymbol{\gamma} \rightarrow \boldsymbol{\delta}$ are abrupt
- Changes in dimensions called ***dilatation*** occur.
  - ***Volume dilatation*** **=** change of volume per unit volume
  - ***Linear dilatation*** **=** change in length per unit length.

SOLUBILITY OF CARBON IN IRON

- Carbon is an interstitial impurity in iron and forms a solid solution with each of α- and δ-ferrites, and also with austenite (γ-iron).

- Diameters of atoms: C = 0.154 nm, Fe = 0.256 nm

- Solubility in **fcc γ-iron** is maximum at 1.7% at 1130°c → ***austenite.***

- Solubility in **bcc phases** are much smaller:

  = 0.1% at 1492°c in bcc *δ*-iron → ***δ-ferrite.***

  = 0.03% at 723°c in bcc *α*-iron → ***α-ferrite*** (generally just termed ***ferrite***).

SOLUBILITY OF CARBON IN IRON

- The limited solubility of carbob in α **-ferrite** is explained by the shape and size of the BCC interstitial positions, which make it difficult to accommodate the carbon atoms.

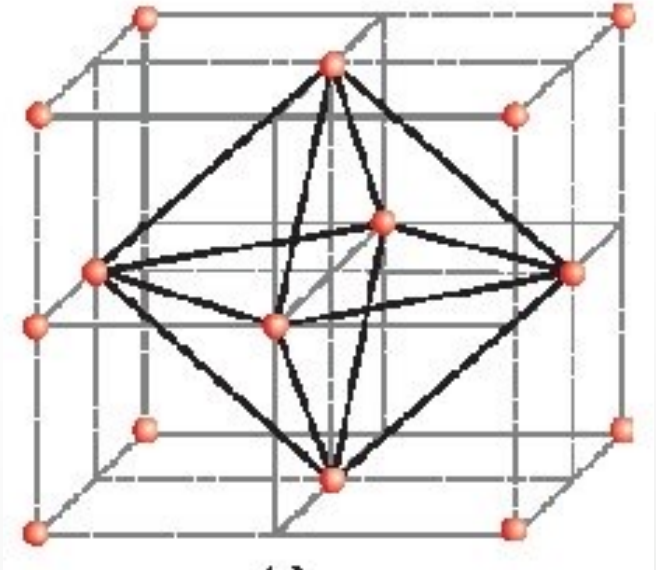
- Even though present in relatively low concentrations, carbon significantly influences the mechanical properties of ferrite..

- This solubility is of carbon in **fcc γ-iron** approximately 100 times greater than the maximum for BCC ferrite, because the FCC interstitial positions are larger and, therefore, the strains imposed on the surrounding iron atoms are much lower.

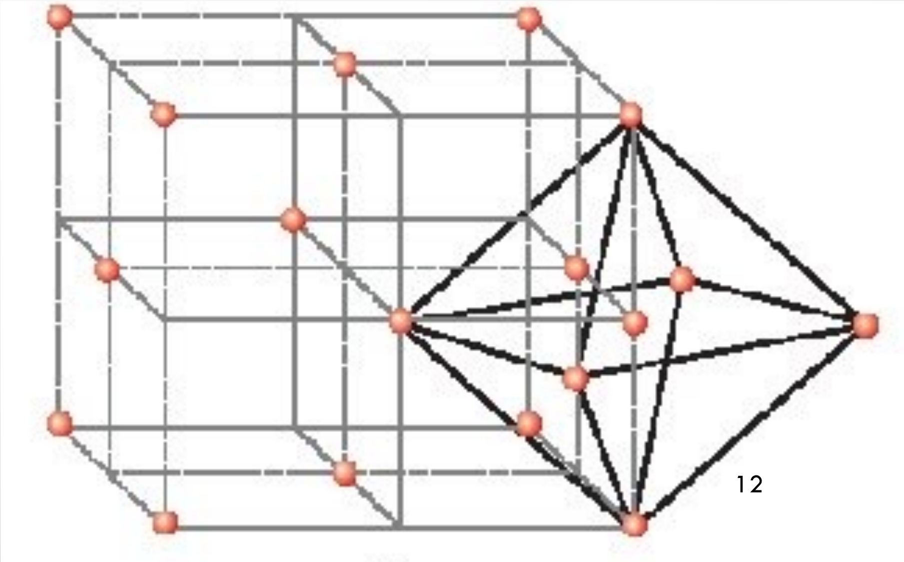
- . The **δ -ferrite** is virtually the same as α -ferrite, except for the range of temperatures over which each exists. Because the δ -ferrite is stable only at relatively high temperatures, it is of very little technological importance.

SOLUBILITY OF CARBON IN FCC AND BCC IRON EXPLAINED

- ❑In fcc, interatomic space is bound by six atoms - octahedral space.
- ❑Expressed as coordinates of the unit cell: the centres of these spaces are at:
  - ✓ (½, ½, ½) – at the body centre of the unit cell (figure a).
  - ✓ (0, 0, ½) – at the centre of each edge (figure b).



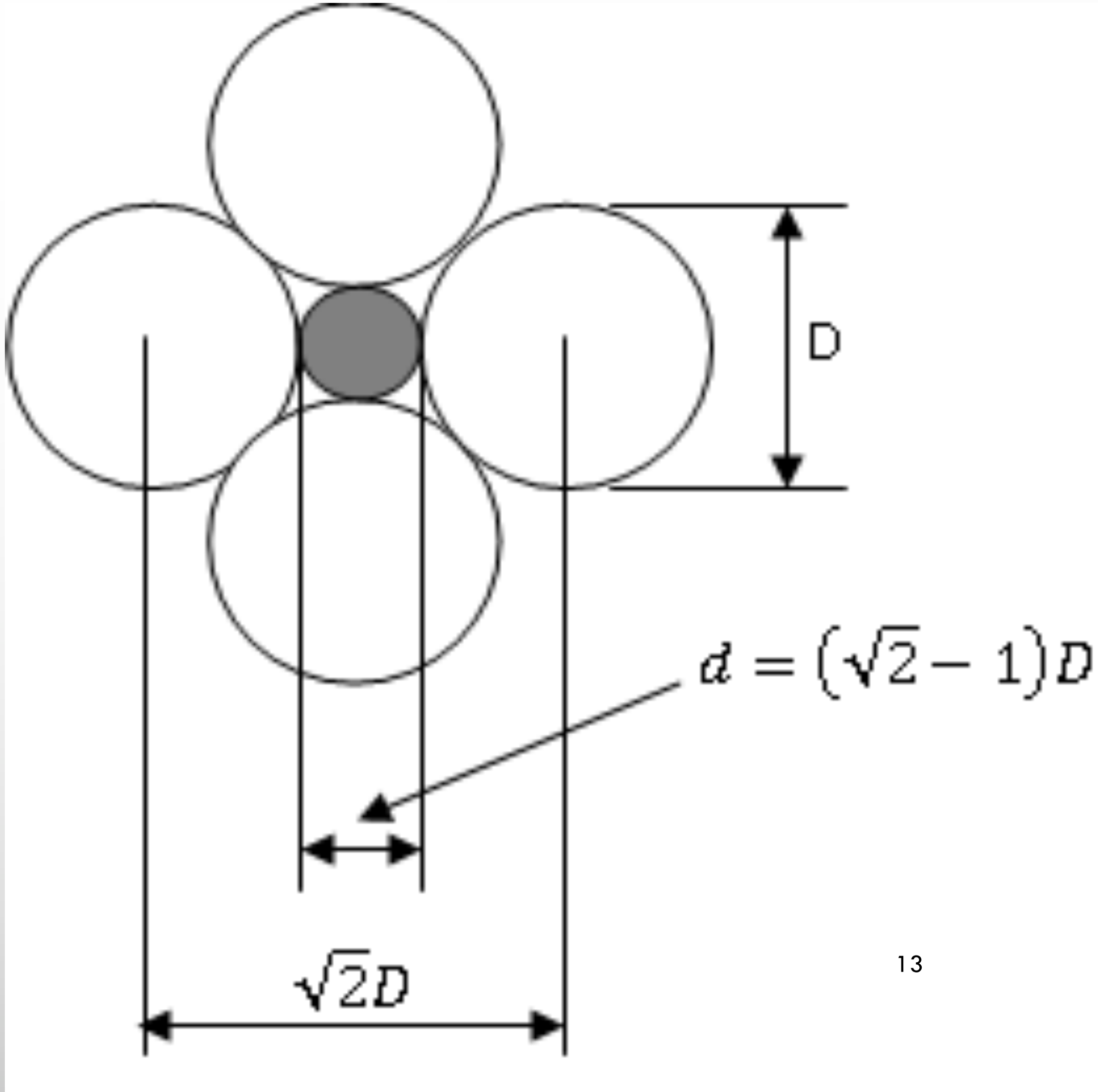
(a)



(b)

SOLUBILITY OF CARBON IN FCC AND BCC IRON EXPLAINED

- Planar view of the octahedral space in the fcc structure,
- D = 0.106 nm
- Thus C (0.154 nm dia), will cause local distortion and stresses in the material lattice.



SOLUBILITY OF CARBON IN FCC AND BCC IRON EXPLAINED

- Thus for 1.7% w/w, the maximum number of C atoms that can go into interstitial solid solution in the γ-iron is about 1 atom to about every 12 spaces available.

(Let the student prove this at home.)

- In the bcc, spaces are not cubical, but have one smaller and two larger dimensions.
- The sphere could be fitted into a space that has coordinates (½, ¼, 0).

SOLUBILITY OF CARBON IN FCC AND BCC IRON EXPLAINED

- And a sphere of diameter of

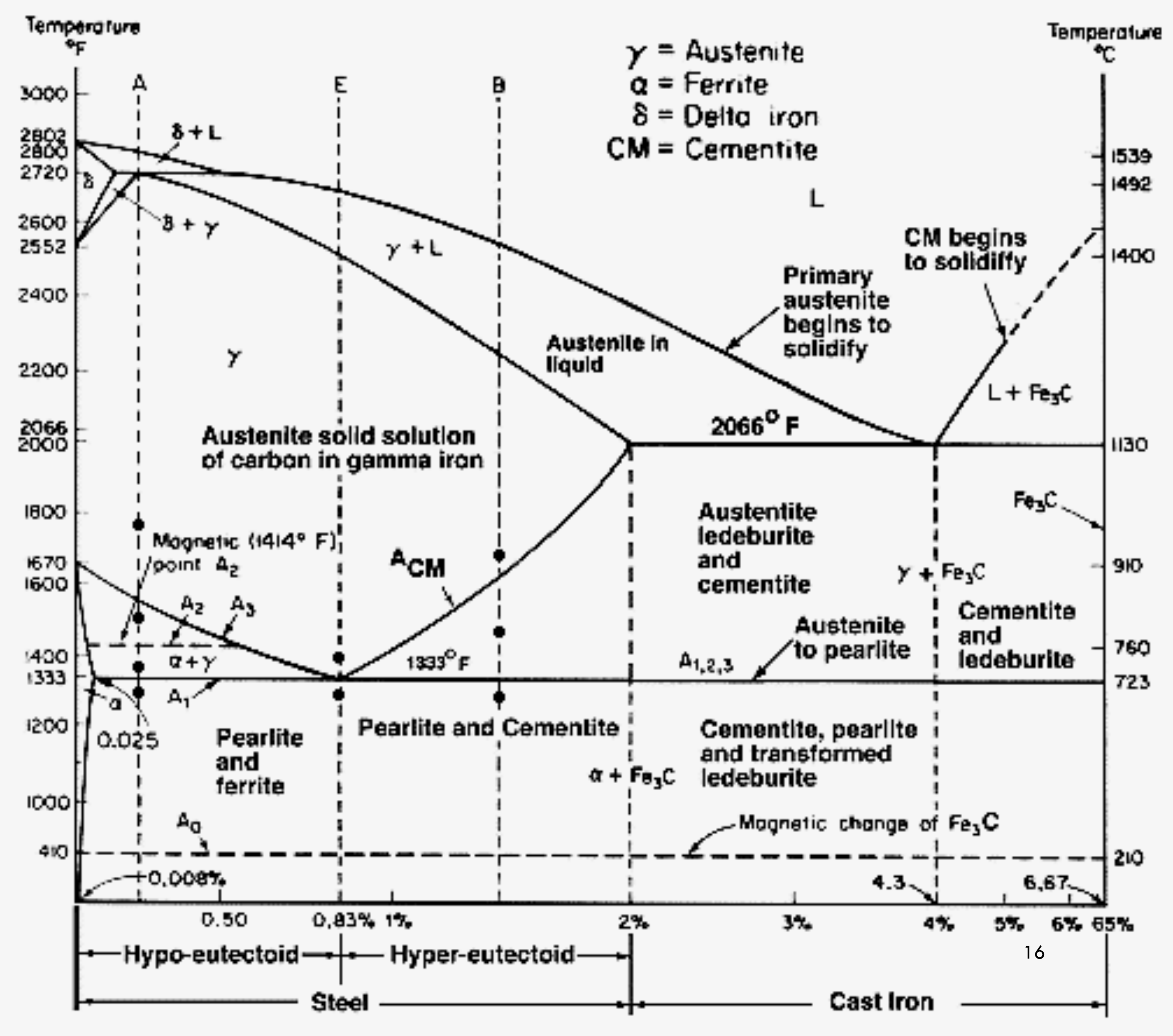
$$d = \left(\sqrt{\frac{5}{3}} - 1\right) D = 0.074\ \text{nm}$$

Can be fitted into the space of the α-iron.

(Let the student prove this at home.)

- Thus, ferrite takes only about 1 carbon atom per 700 spaces at maximum solubility!

THE IRON-CARBON SYSTEM



(PURE) PHASES IN THE IRON-CARBON SYSTEM

- ***Ferrite or alpha-iron phase (α-iron)*** – It is a stable form of iron at room temperature. It is relatively soft low temperature phase and is a stable equilibrium phase. It is soft, and fairly ductile. It is magnetic below 768 deg C. It has low strength and good toughness.

- ***Austenite or gamma iron phase (γ-iron)*** – Austenite is a high temperature phase. It is a solid solution of C in the FCC iron.. It is a non magnetic and ductile phase. It is not stable below the eutectic temperature (727 deg C) unless cooled rapidly. Austenite has good strength and toughness.

- ***Delta ferrite phase (δ-iron)*** – It is solid solution of C in BCC iron. It is stable only at temperature higher than 1394 deg C.. It has paramagnetic properties.

- ***Cementite*** = intermediate compound of iron and carbon at 6.67% C w/w, the formula $\mathbf{Fe_3C}$. Also called Iron Carbde, It has a complex orthorhombic structure and is a metastable phase. It is a hard, brittle phase. It has low tensile strength, good compression strength and low toughness. It decomposes (very slowly, within several years) into alpha ferrite and C (graphite) at the temperature range of 650 deg C to 700 deg

EUTECTIC AND EUTECTOID MICROSTRUCTURE IN THE IRON-CARBON SYSTEM

LEDEBURITE

- Between iron (austenite) and cementite, is a **eutectic** at 4.3% C and 1130°c.
- The eutectic is between austenite and cementite and is called ***ledeburite*** - commercially called ***pig iron***.

PEARLITE

- Alloy of eutectoid composition (0.83 % C) when **cooled slowly**, forms **pearlite**, which is a layered structure of two phases namely alpha-ferrite and cementite and is a ferrite-cementite phase mixture.
- Mechanically, the pearlite has properties intermediate to soft, ductile ferrite and hard, brittle cementite. It has high strength and low toughness.

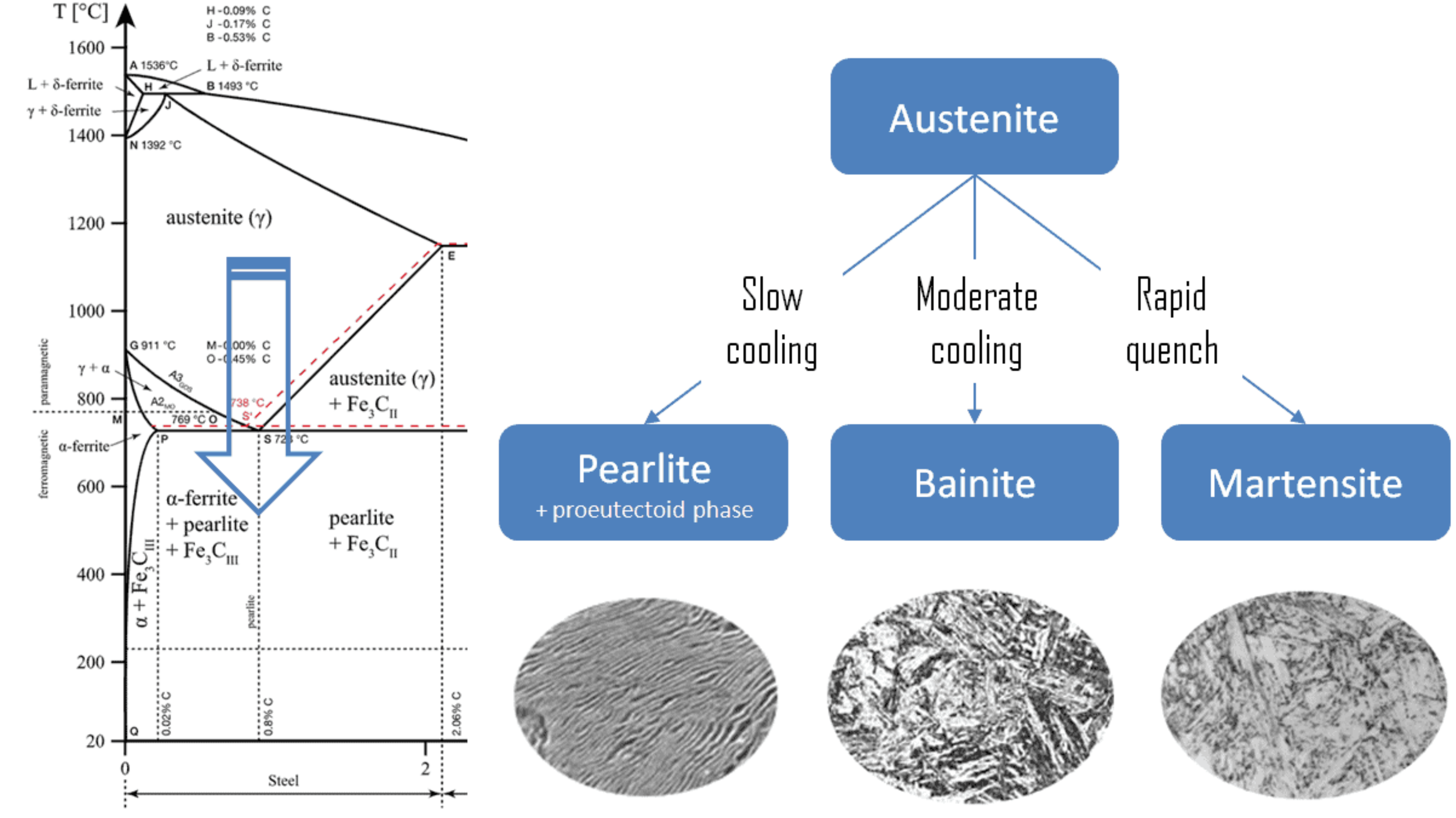
OTHER MICROSTRUCTURE AND PHASES IN THE IRON-CARBON SYSTEM

- **MARTENSITE**
- Martensite is formed by **rapid cooling** of austenite and is hard, brittle, high strength and low toughness. It is a **body-centered tetragonal (BCT)** form of iron in which some carbon is dissolved.
- It is formed during quenching, when the FCC lattice of austenite is distorted into the BCT structure without the loss of its contained carbon atoms into cementite and ferrite. It is a super saturated solid solution of C atoms in ferrite. It is a hard metastable phase.

BAINITE

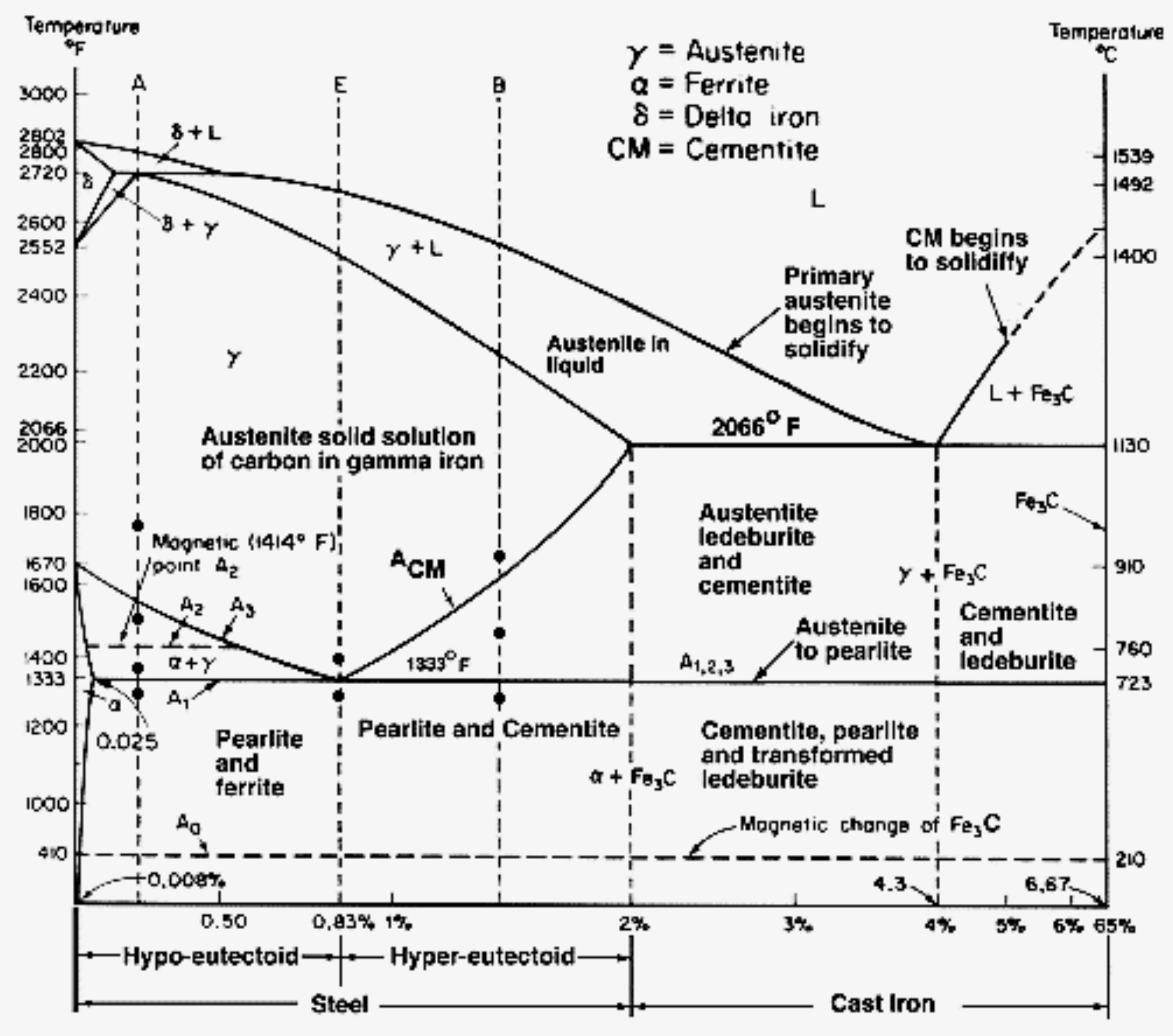
- It is a structure between **pearlite and martensite**. Bainite is a plate-like microstructure that forms in steels from austenite when cooling rates are not rapid enough to produce martensite but are still fast enough so that carbon does not have enough time to diffuse to form pearlite.
- Bainitic steels are generally stronger and harder than pearlitic steels; yet they exhibit a desirable combination of strength and ductility..

OTHER MICROSTRUCTURE AND PHASES IN THE IRON-CARBON SYSTEM



THE IRON-CARBON SYSTEM

- Greatest solubility of C in austenite is 1.7% at the eutectic temperature (1130ºc)
- Above and below this temperature, solubility decreases.
- Above 0.2% C, on heating, limit of solubility is reached, at the solidus → two-phase (austenite + liquid) region.
- Above 0.83% C, on cooling, cementite precipitates when limit of solubility is reached.

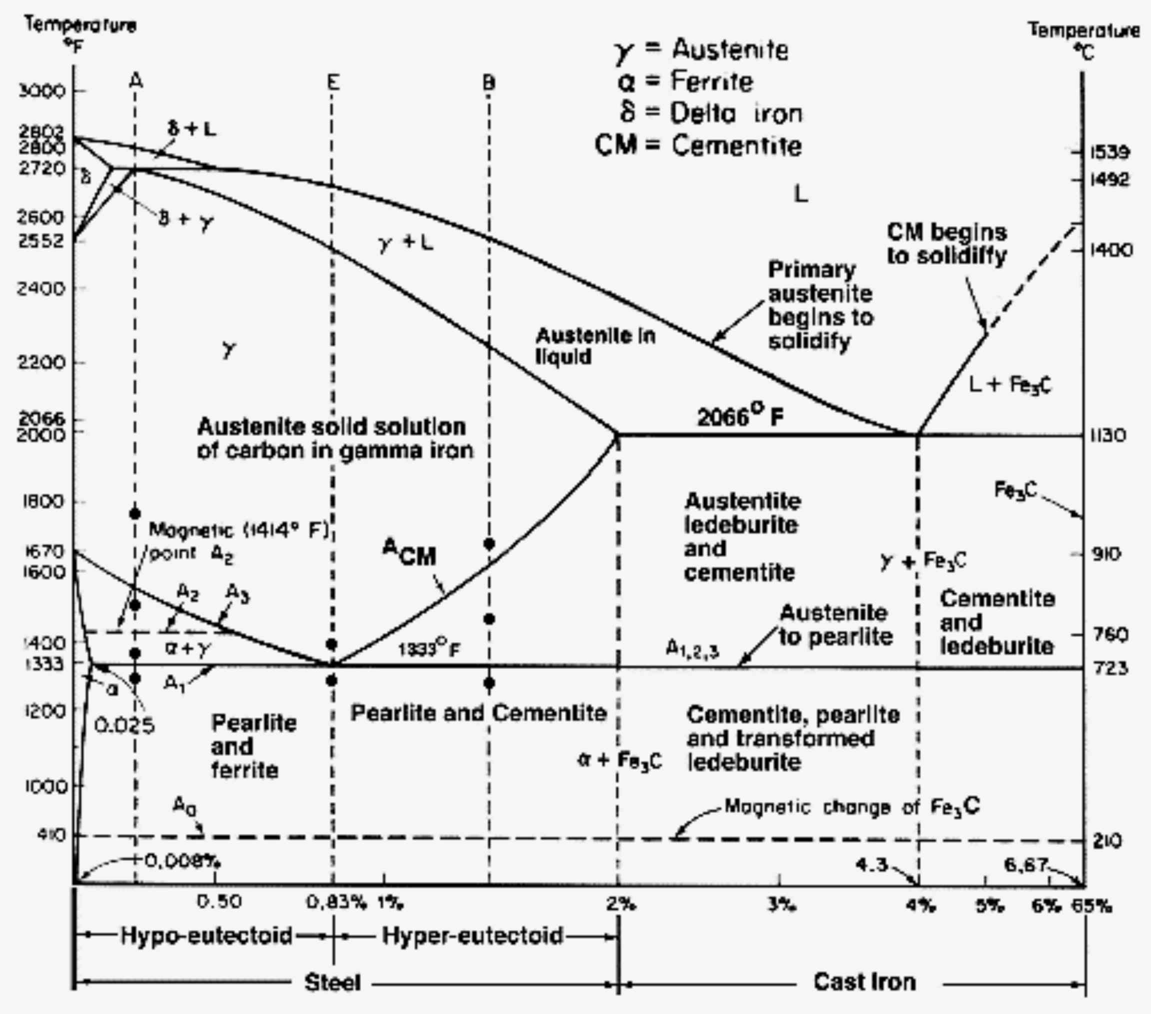


MODIFICATION OF ALLOTROPIC CHANGE TEMPERATURES

- Austenite - higher solubility for C than either ferrite or δ-iron.
  - Result: presence of C raises the temperature of the $\gamma \rightarrow \delta$ change and lowers that of the $\gamma \rightarrow \alpha$ change – increasing austenite temperature range with increase in C content.
- On cooling, say, 0.3% C alloy from austenite: change to ferrite begins at about 850^{o}c - ferrite crystals nucleate on austenite grain boundary.

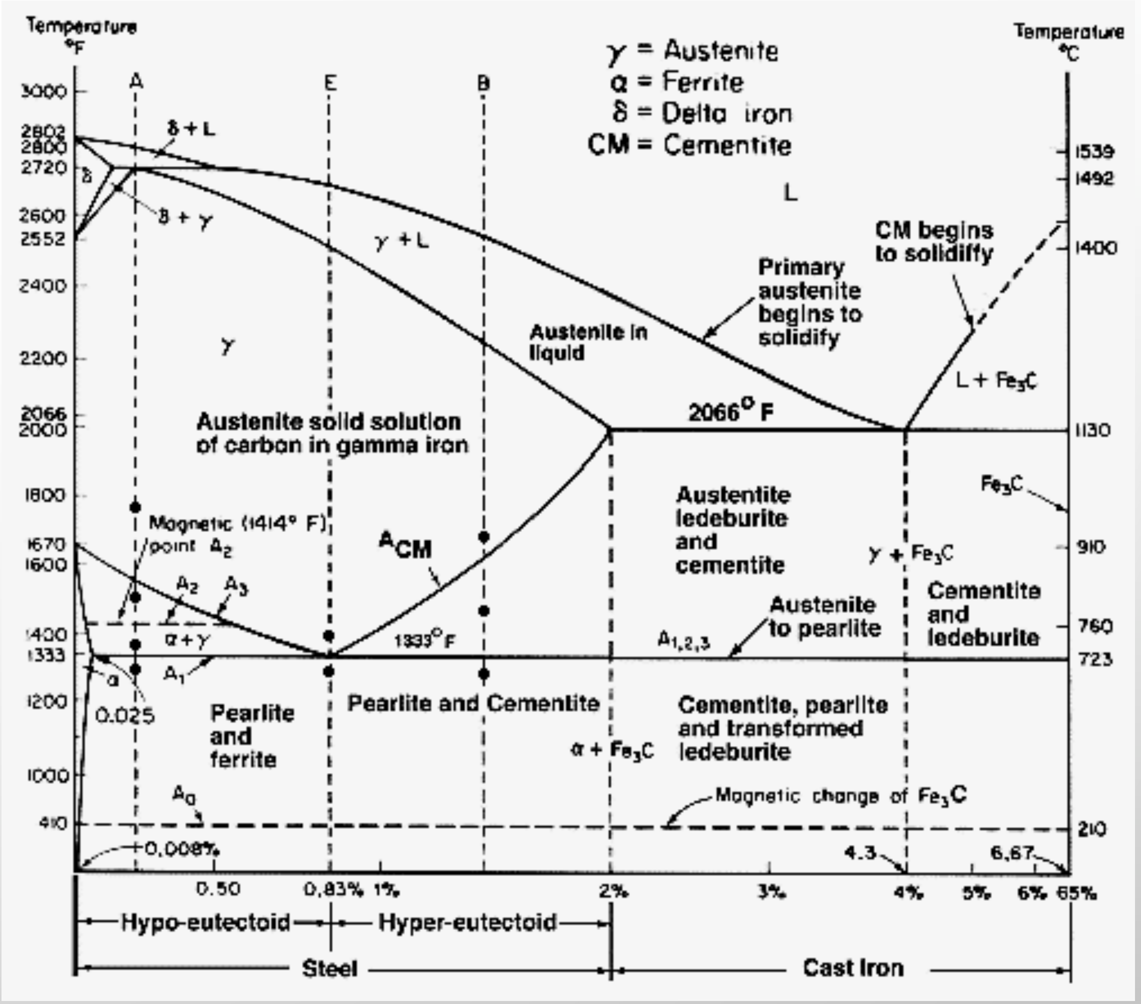
THE IRON-CARBON SYSTEM

- Lower boundary of austenite region is formed by two lines:
  - One from 910 °c at pure iron – **the ferrite separation line**.
  - The other from 1130°c (taken up to 1147°c) at 1.7% (up to 2%) C – **the cementite separation line**.
  - The lines intersect, showing a ***eutectoid*** reaction at 723°c (up to 727°c) between 0.80 and 0.83% c. (Sometimes up to 0.90% c).
  - The ***eutectoid*** formed is called ***pearlite***.

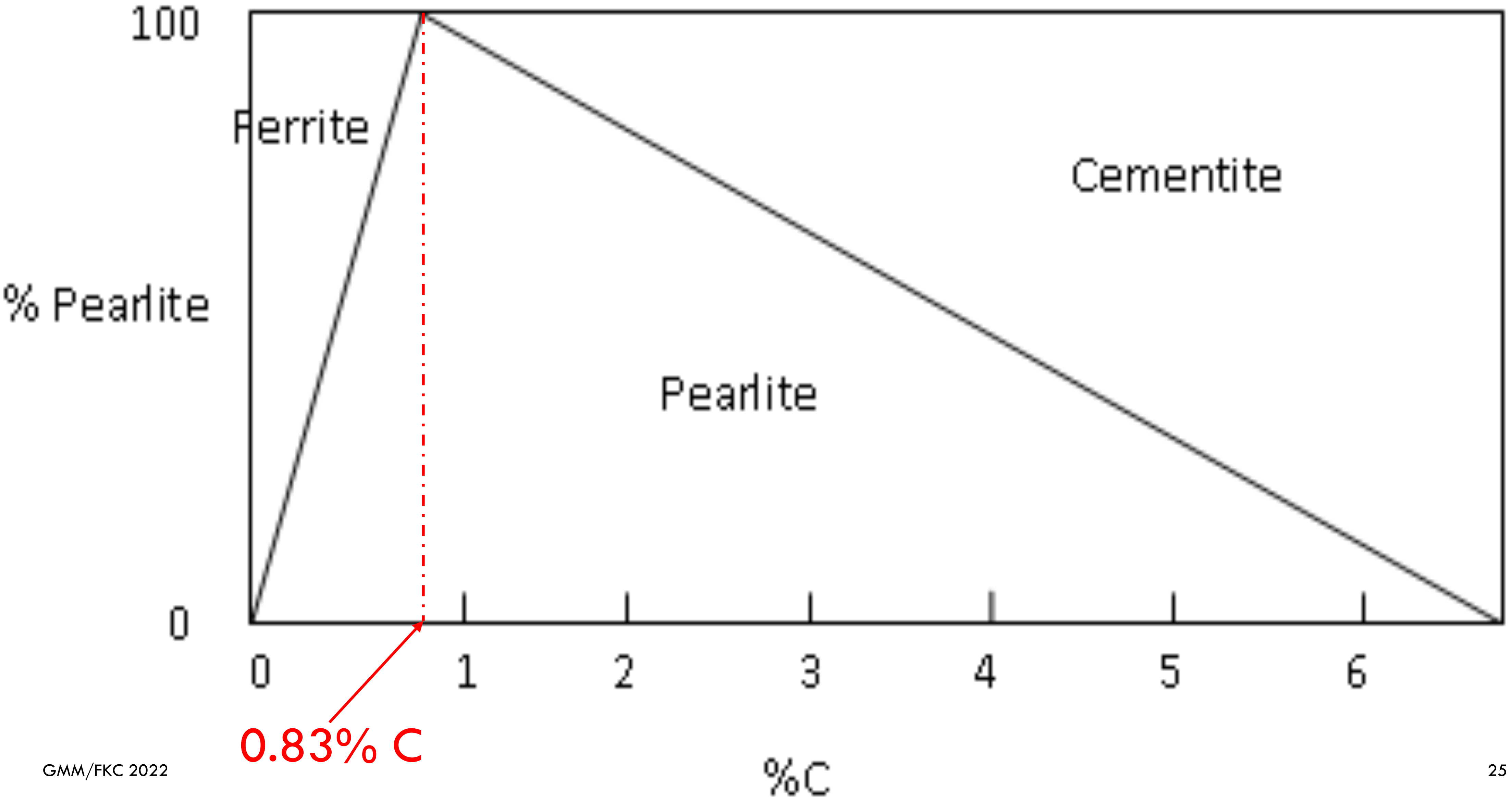


THE IRON-CARBON SYSTEM

- The eutectoid, ***pearlite***, forms as precipitation of ferrite and cementite (laminated flakes of cementite and ferrite).
- Pearlite = (0.83/6.67)x100 = 12.4% cementite and 87.6% ferrite.
- Structure of any alloy at room temperature would be:
  - Part ferrite and part pearlite for 0.83% < c
  - Part pearlite and part cementite for C > 0.83%

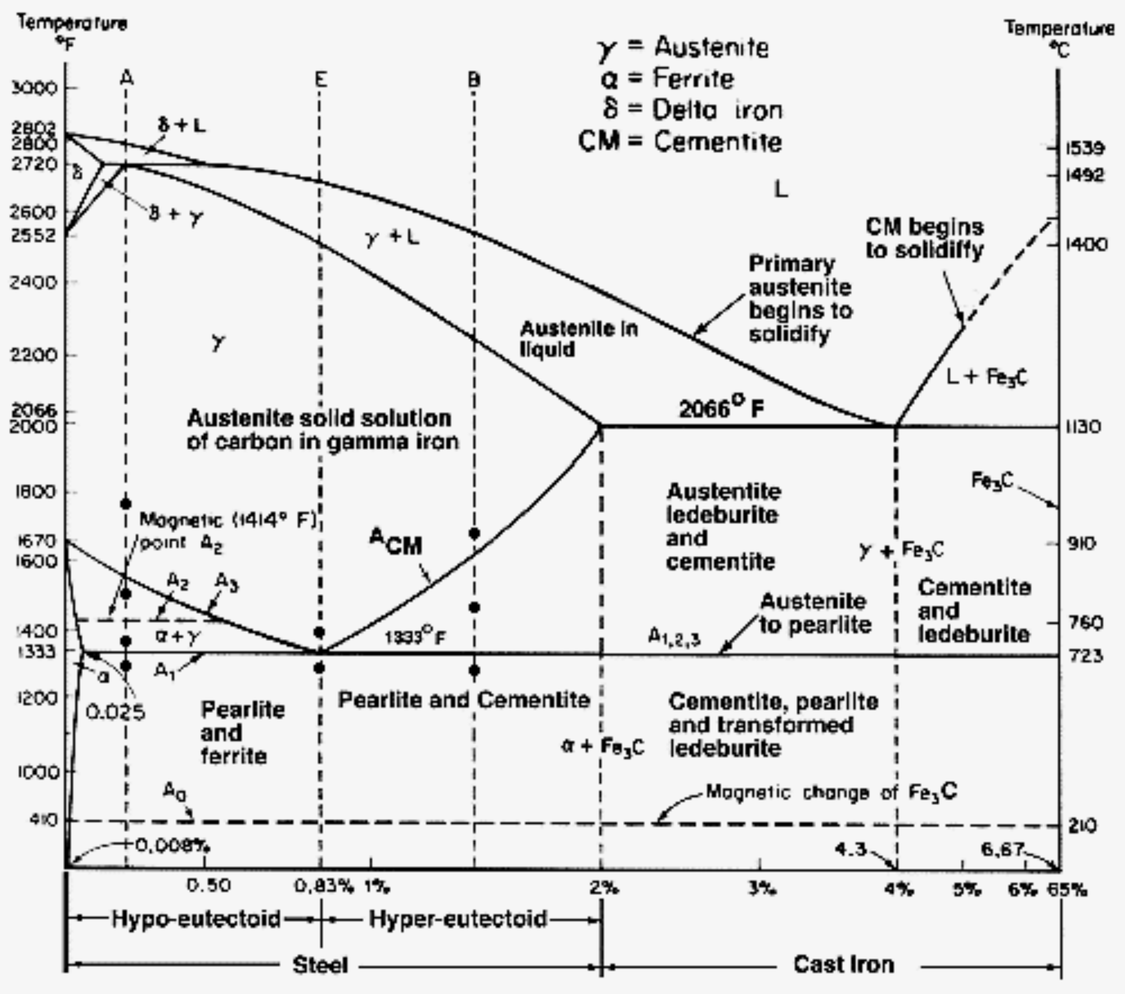


THE IRON-CARBON SYSTEM



THE IRON-CARBON SYSTEM

- Upper boundary of austenite region is formed by two lines:
  - One from 1400ºc at pure iron – the δ-ferrite separation line.
  - The other from 1130ºc at 1.7% C – the cementite separation line.
  - The lines intersect, showing a ***peritectic*** reaction at 1492ºc (up to 1493ºc) at about 0.18% c. (Sometimes taken as much as 0.20% c).



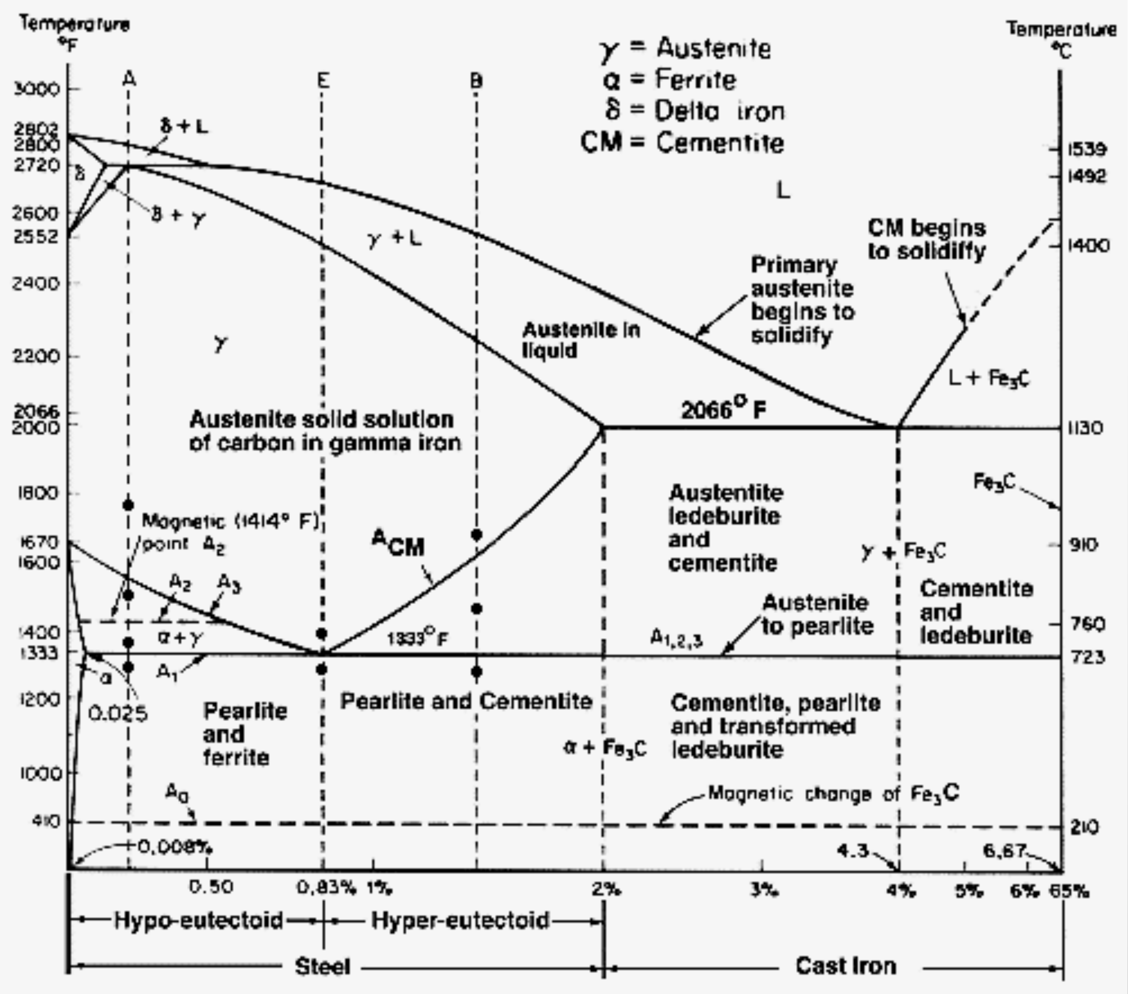
THE IRON-CARBON SYSTEM

Thus:

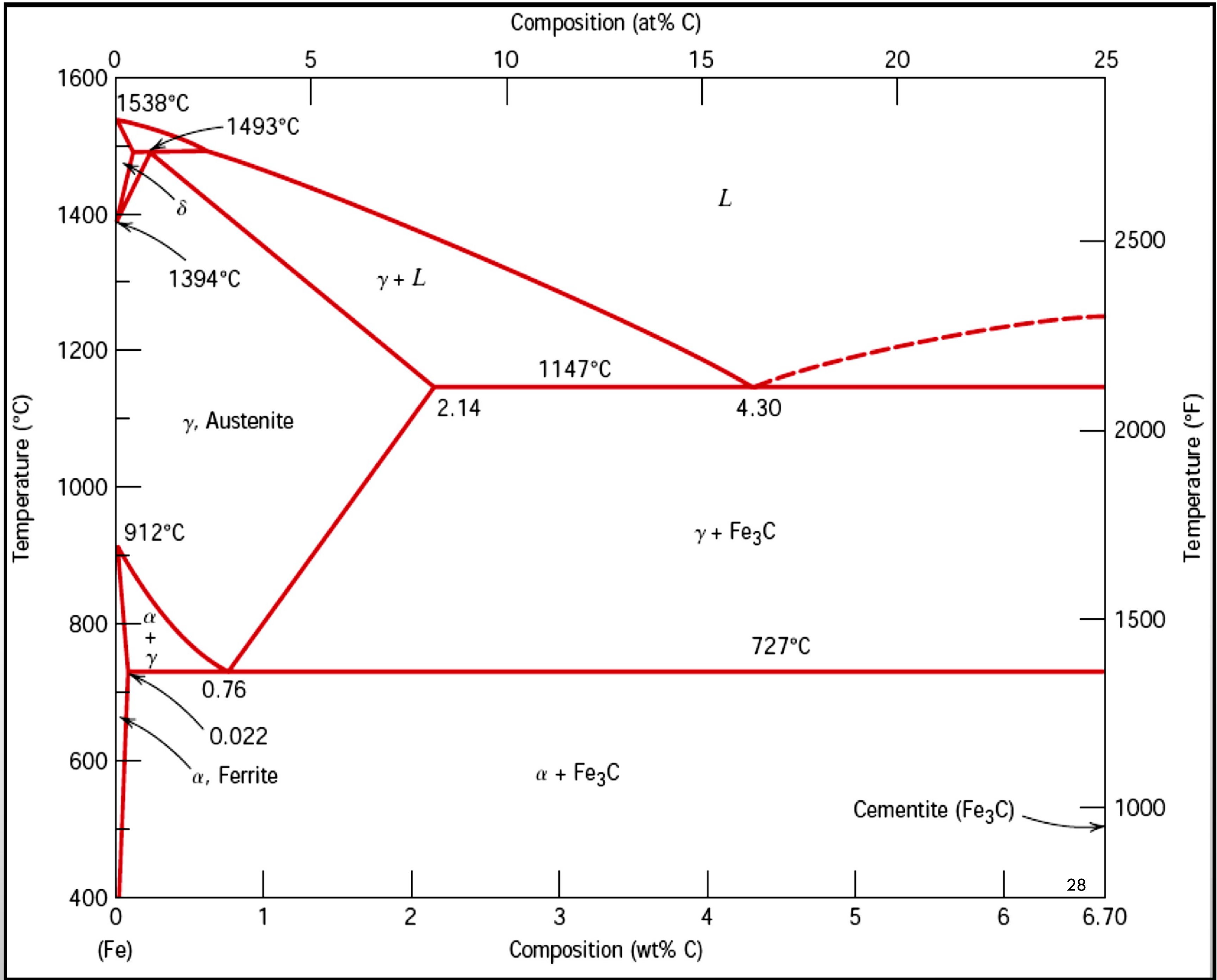
- The upper part of ***austenite*** region terminates in a ***peritectic*** reaction at 1492°c at 0.18% c;

While

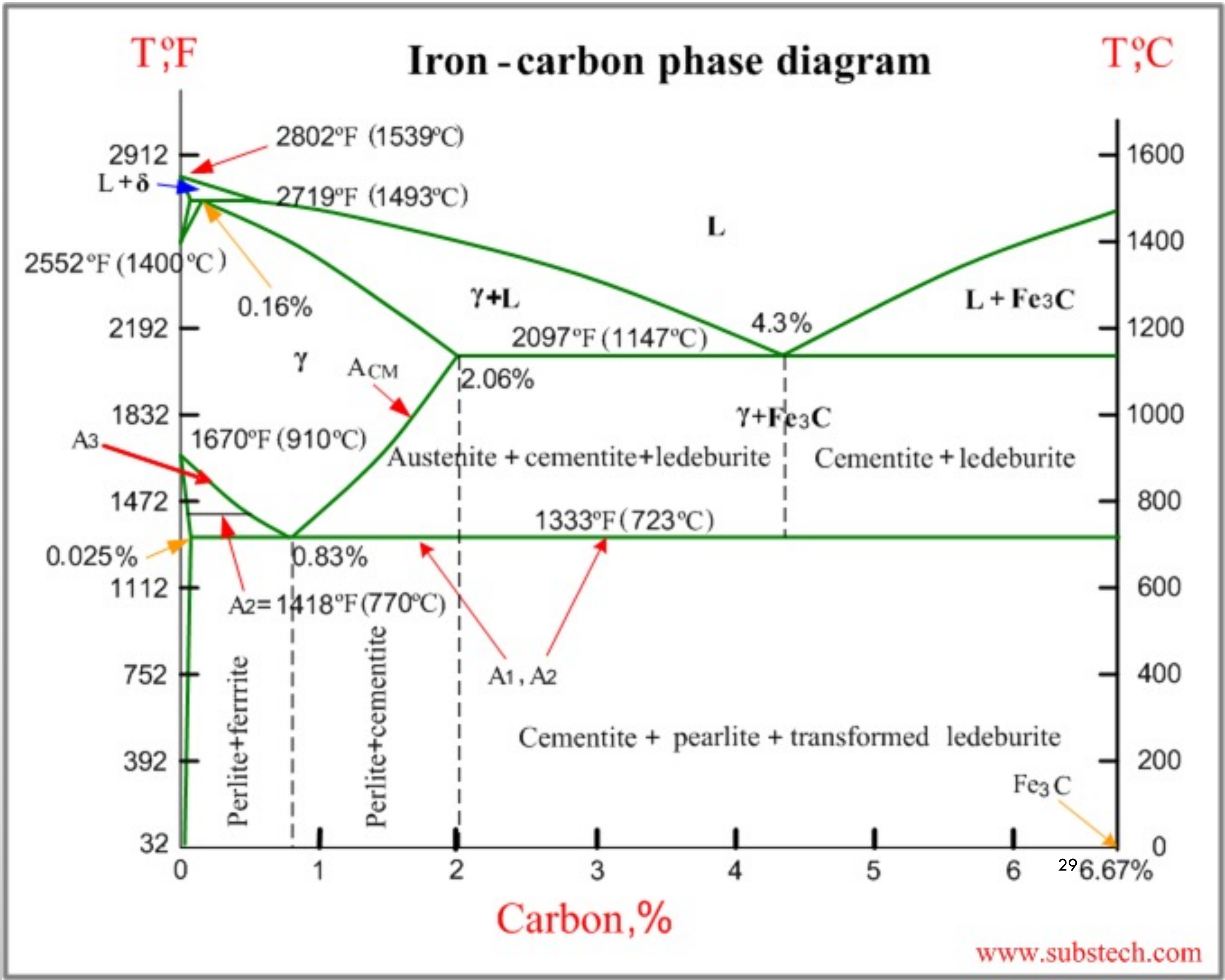
- The lower part of ***austenite*** region terminates in a ***eutectoid*** reaction at 723°c at 0.83% c.



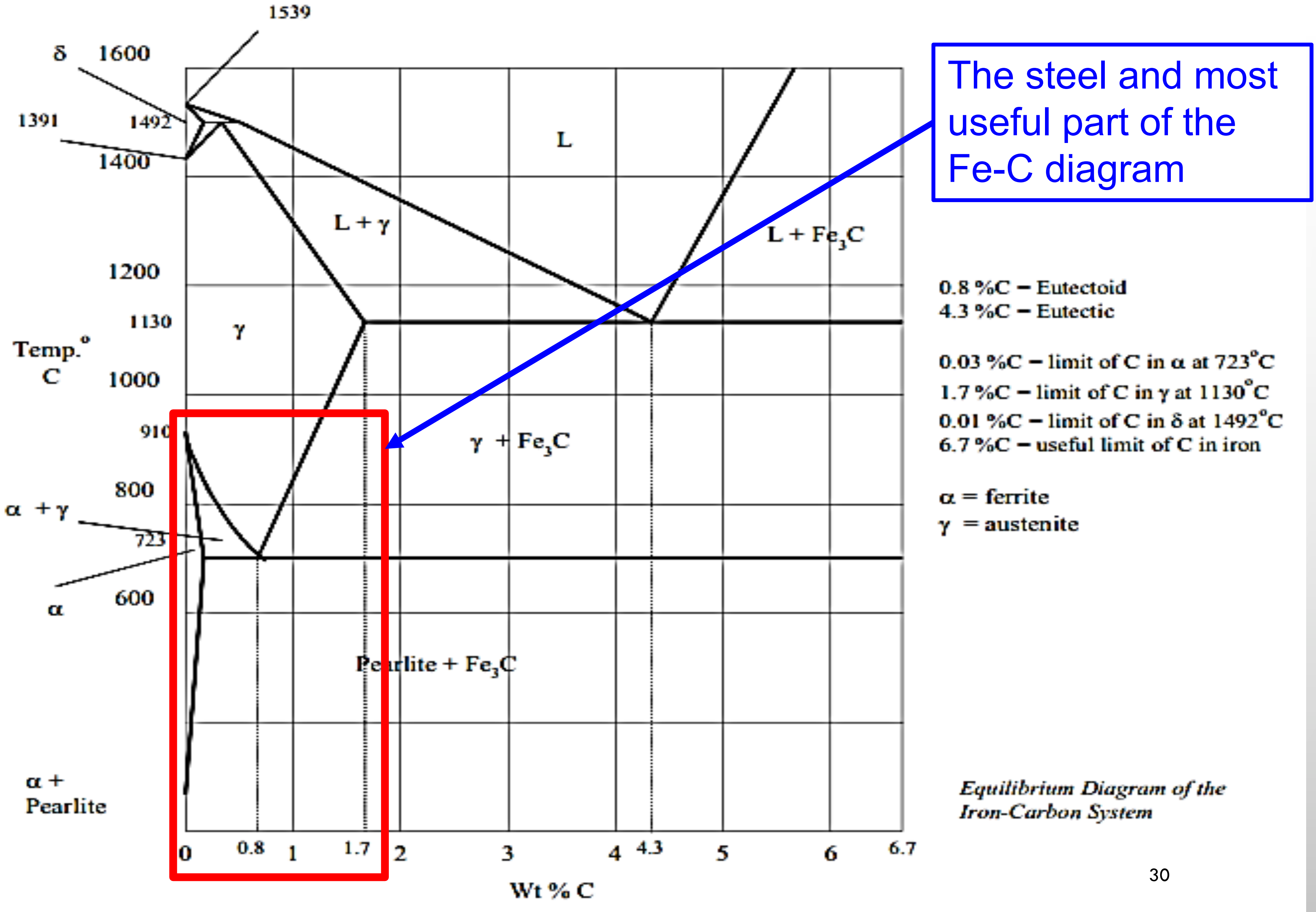
THE IRON-CARBON SYSTEM PHASE DIAGRAM VARIETIES



THE IRON-CARBON SYSTEM PHASE DIAGRAM VARIETIES



THE SIMPLIFIED IRON-CARBON SYSTEM



Equilibrium Diagram of the Iron-Carbon System

RELATIONSHIP BETWEEN FAHRENHEIT (^{O}F) AND CELSIUS (^{O}C) TEMPERATURES

$$^{o}\mathrm{F} = {}^{o}\mathrm{C} \times \frac{9}{5} + 32$$

AND

$$^{o}\mathrm{C} = ({}^{o}\mathrm{F} - 32) \times \frac{5}{9}$$

SOME TEMPERATURE COMPARISONS:

Freezing/melting point of water = 0^{o}C = 32^{o}F

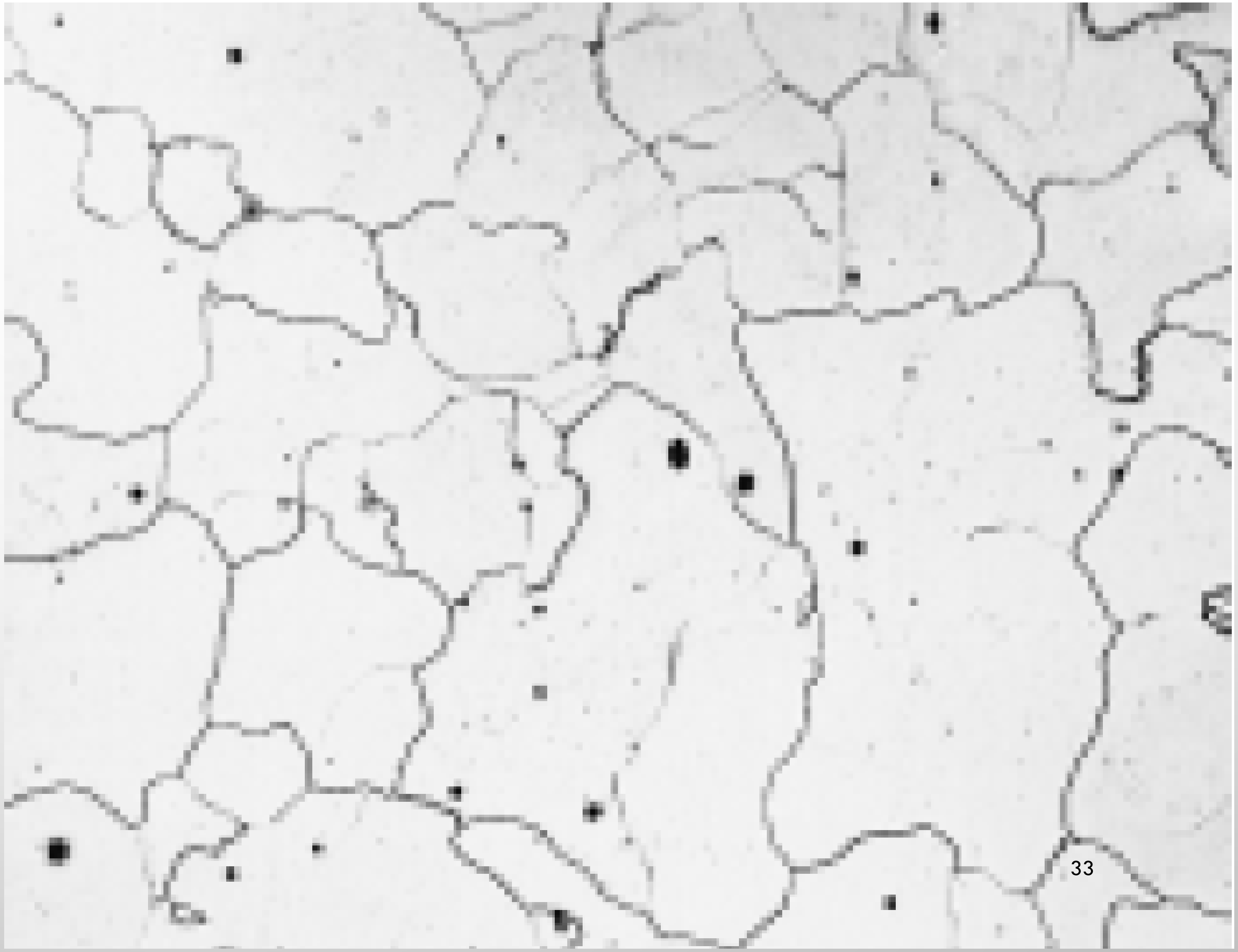
Boiling point of water = 100^{o}cC = 212^{o}F

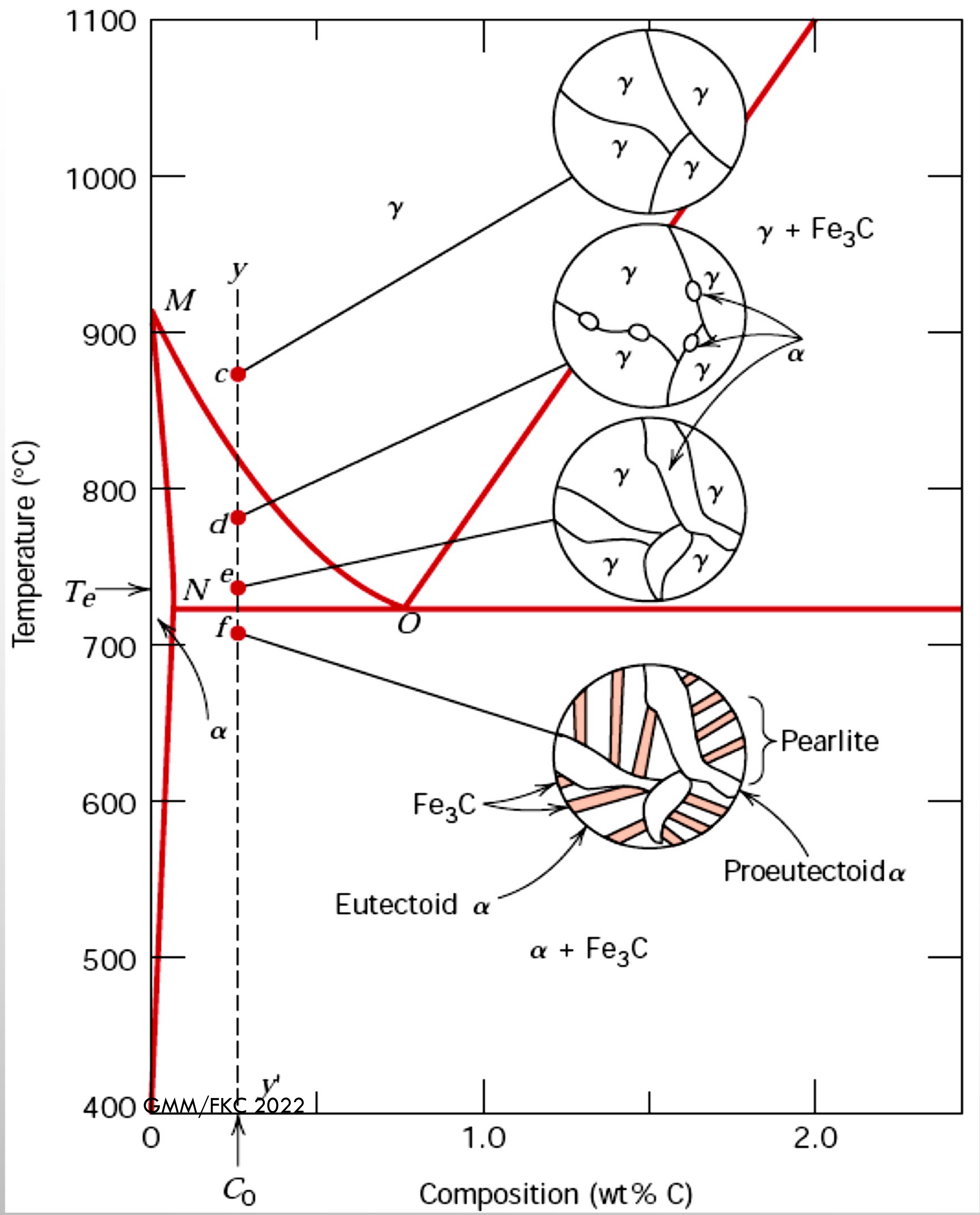
NOMENCLATURE OF IRON CARBON ALLOYS

- An alloy with less than 0.03% C (entirely ferrite at 723^{o}c) → usually referred to as ***pure iron***.
- 0.03% c – 1.7% C (entirely austenite at 1130^{o}c) → ***steels***, further divided as:
  - ***Hypoeuctoid steels*** (0.03 – 0.83% C) and
  - ***Hypereutctoid steels*** (above 0.83 – 1.7% c)
- 1.7% c – 6.67% C → ***cast irons***.

PURE IRON

Pure irons (ferrite only) show sharp grain boundaries



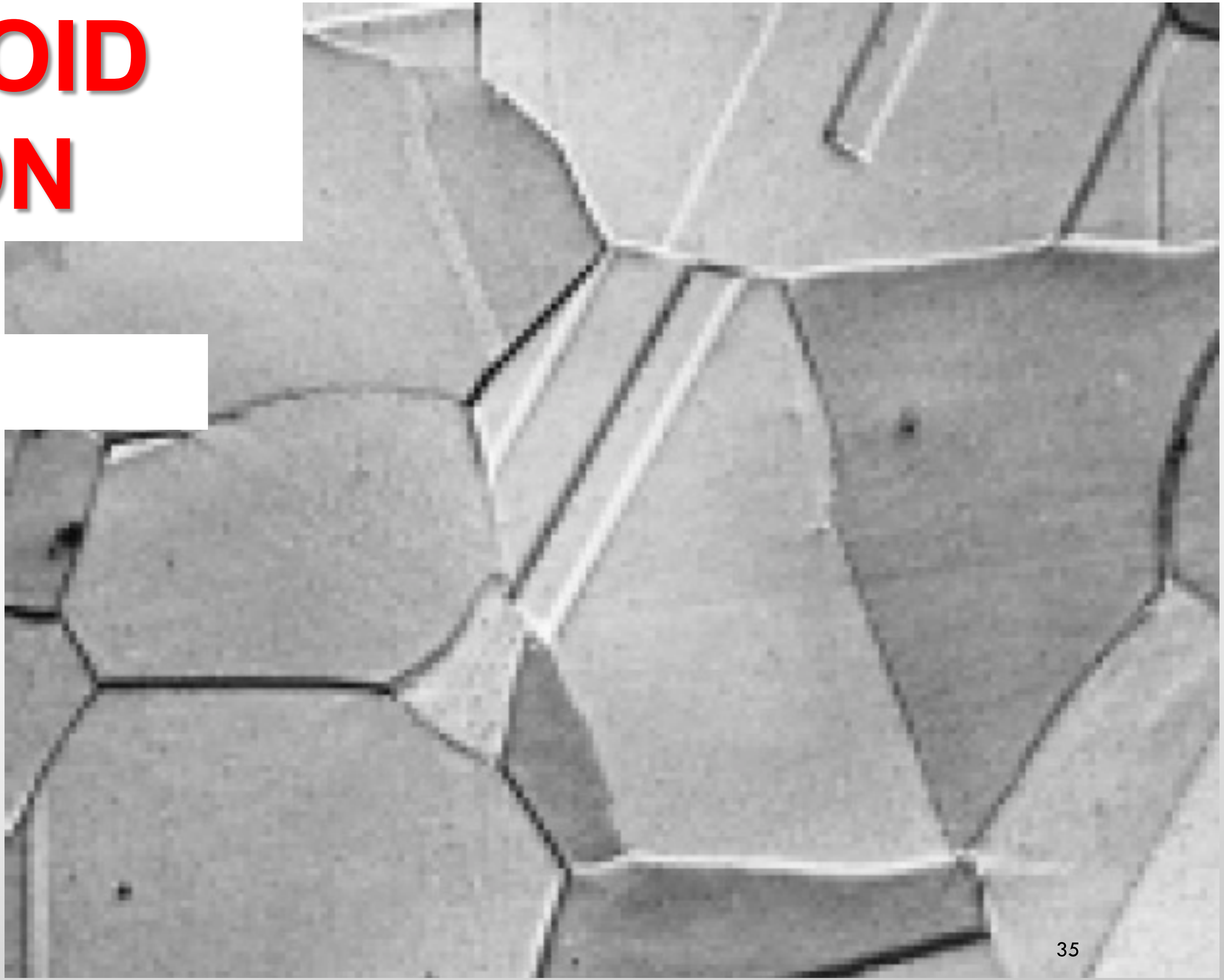


HYPOEUTECTOID COMPOSITION

Hypoeutectoid composition (0.76% C) as cooled from the austenite region to below the eutectoid temperature

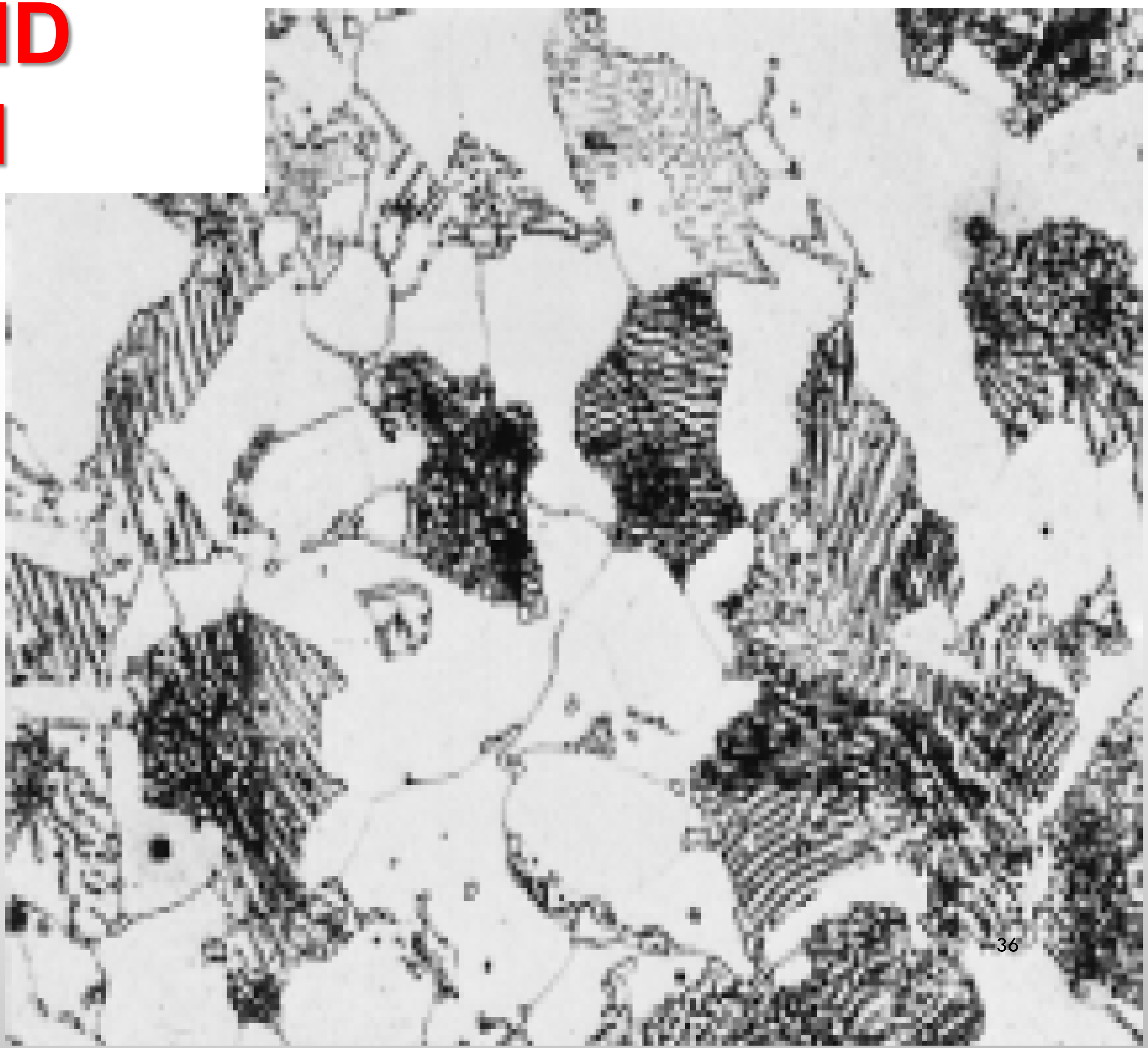
HYPOEUTECTOID COMPOSITION

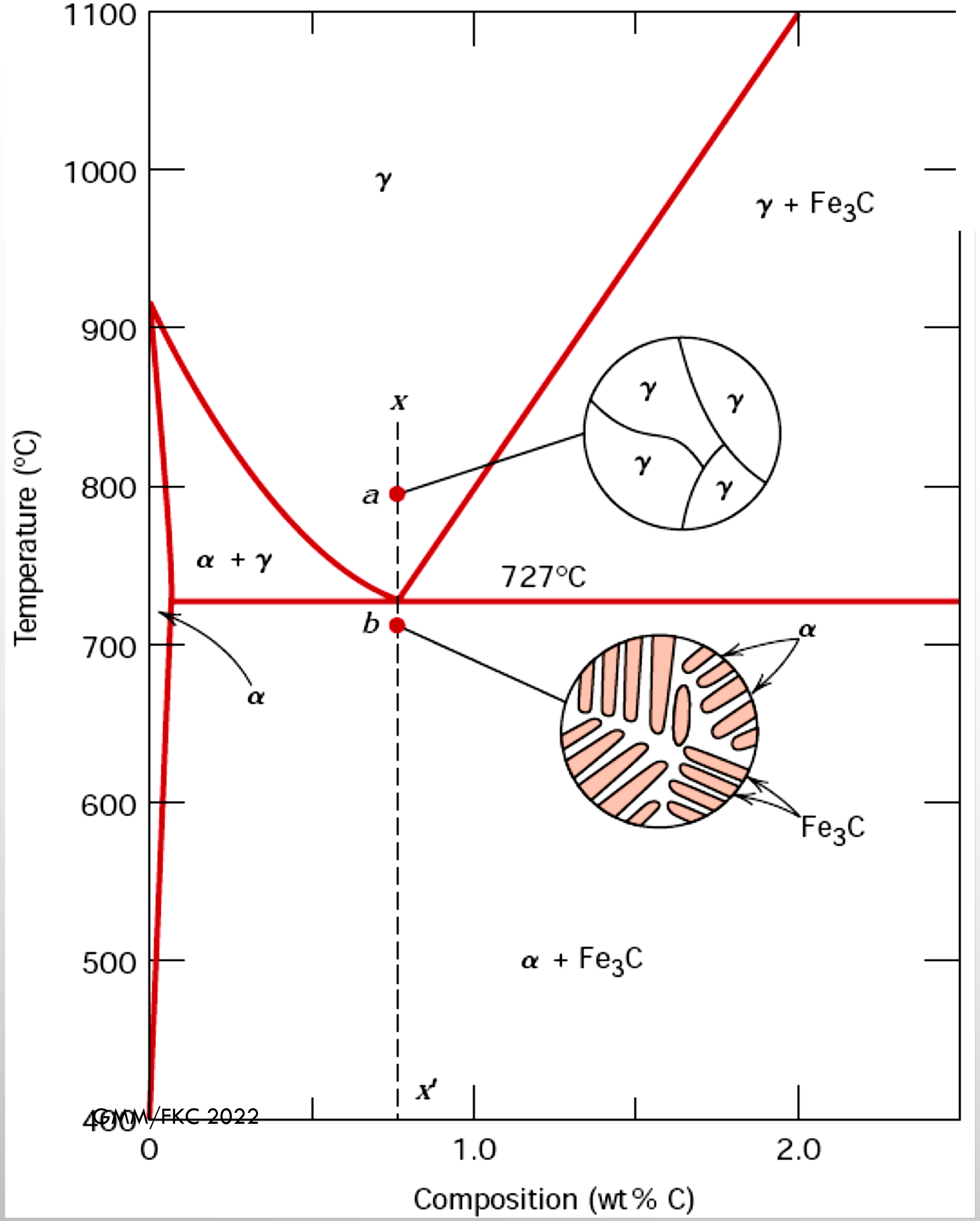
AUSTENITE



HYPOEUTECTOID COMPOSITION

With increase in C content, (0.38% C) pearlite increases & appears dark or striped and can be distinguished clearly from the light ferrite



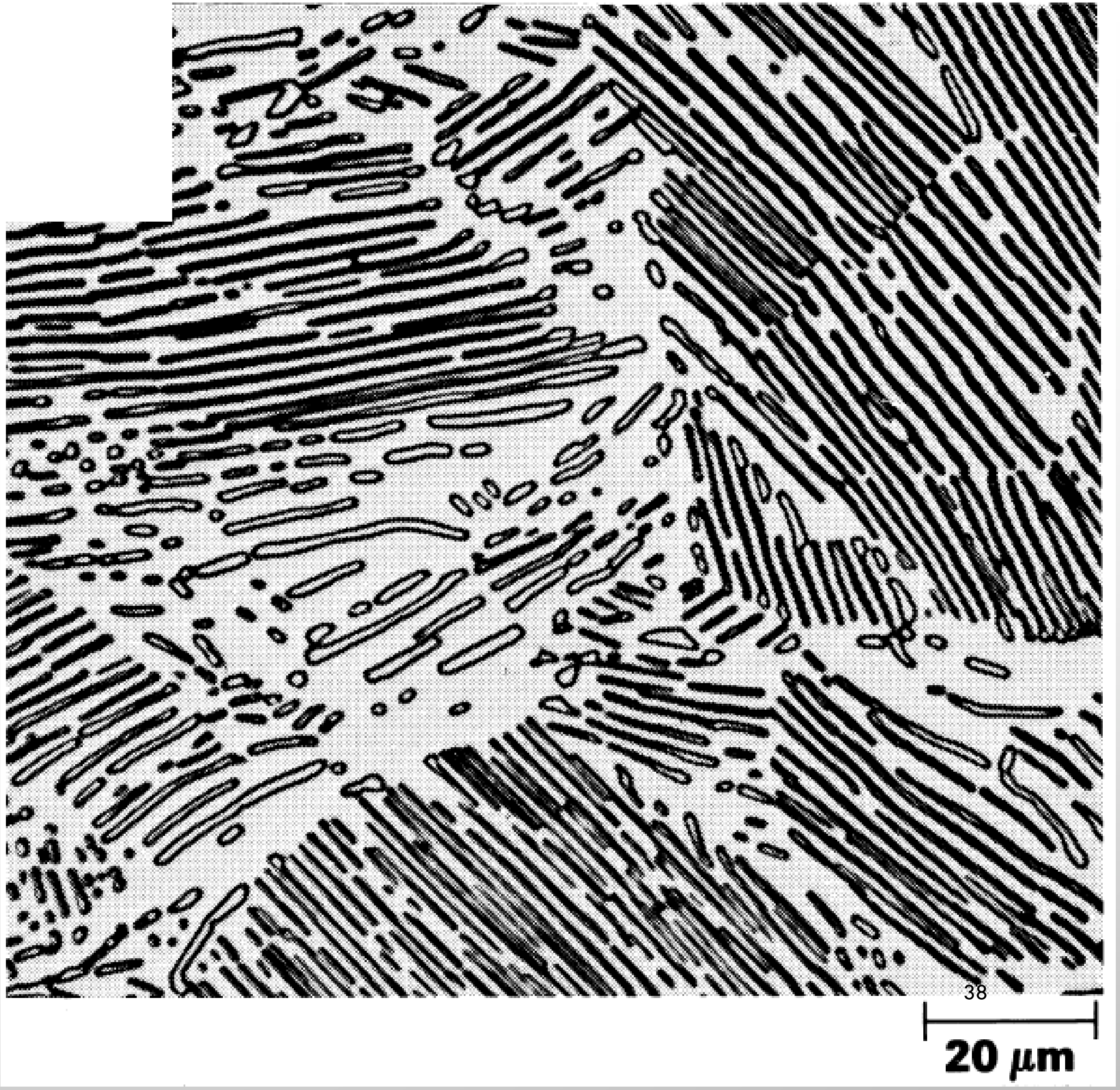


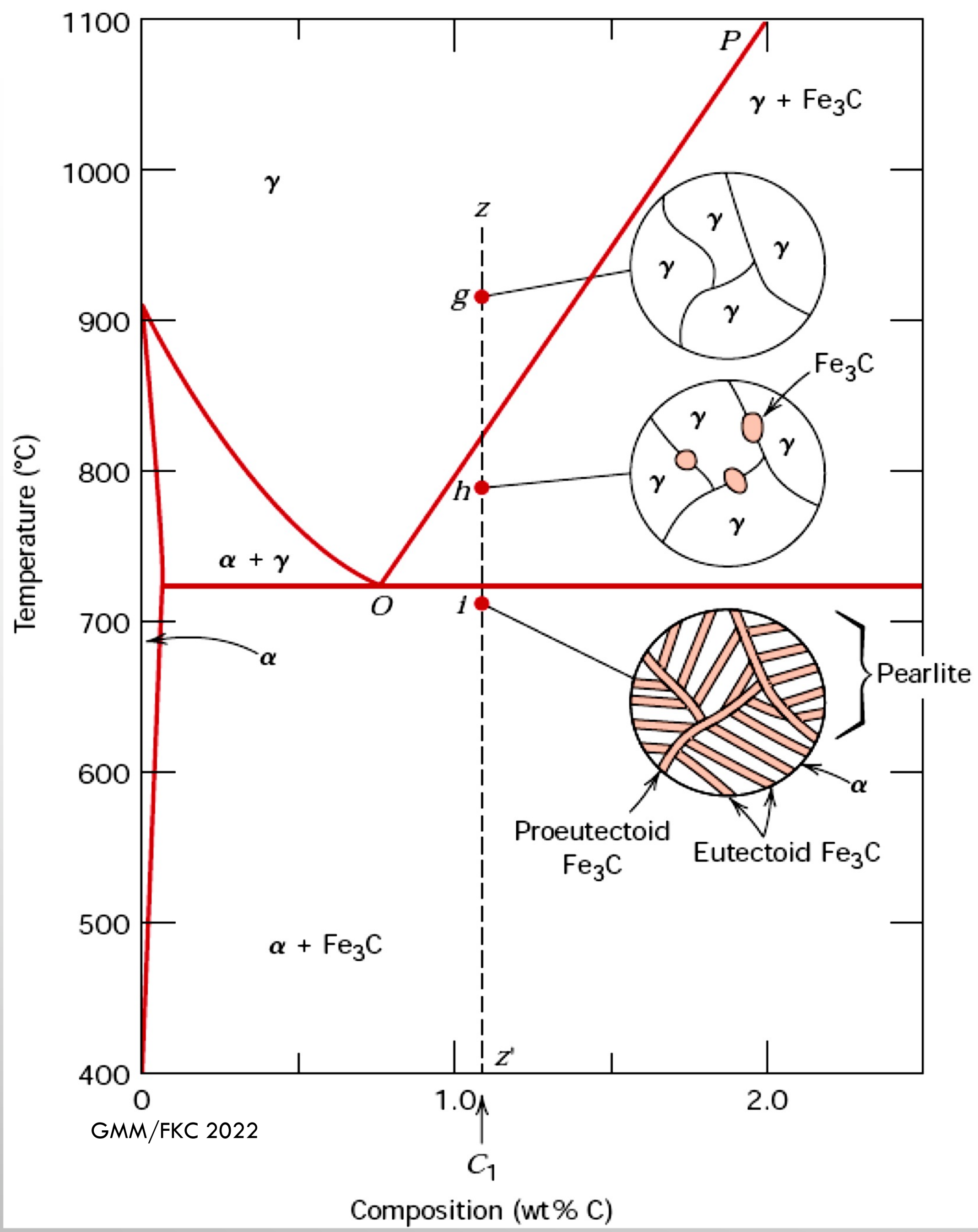
EUTECTOID COMPOSITION

Eutectoid composition – above and below the eutectoid temperature

EUTECTOID COMPOSITION

Eutectoid steel showing the pearlite microstructure consisting of alternating layers of ferrite (light phase) and cementite (dark phase).





HYPEREUTECTOID COMPOSITION

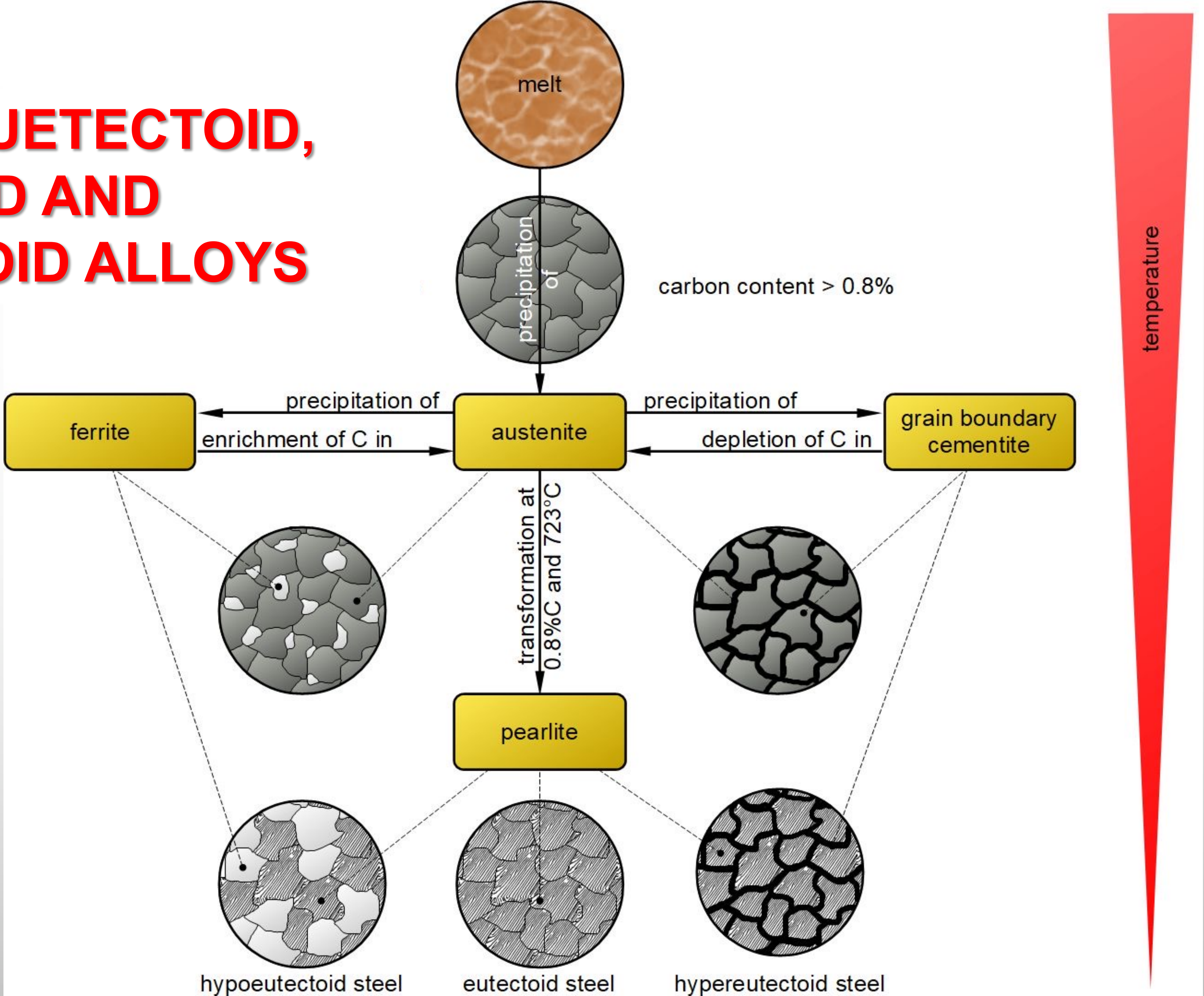
Hypereutectoid composition – above and below eutectoid temperature

HYPEREUTECTOID COMPOSITION

With increase in C content, pearlite increases in quantity appears dark or striped and may be distinguished clearly from the ferrite.

(1.4% C Steel - white hypoeutectoid cementite network surrounding the pearlite colonies.

SUMMARY: HYPUETECTOID, EUTECTOID AND HYPEREUTECTOID ALLOYS



CAST IRONS

- **Cast irons** = all fe-c alloys with C > 1.7% c.
- Never single-phase on first solidification – always contain some cementite.
- Changes on cooling are complex
- Final structure = **mixture of ferrite + cementite**.
- In hypereutectic alloys - some graphite forms from the liquid
- Cast iron containing cementite = **white cast iron**.

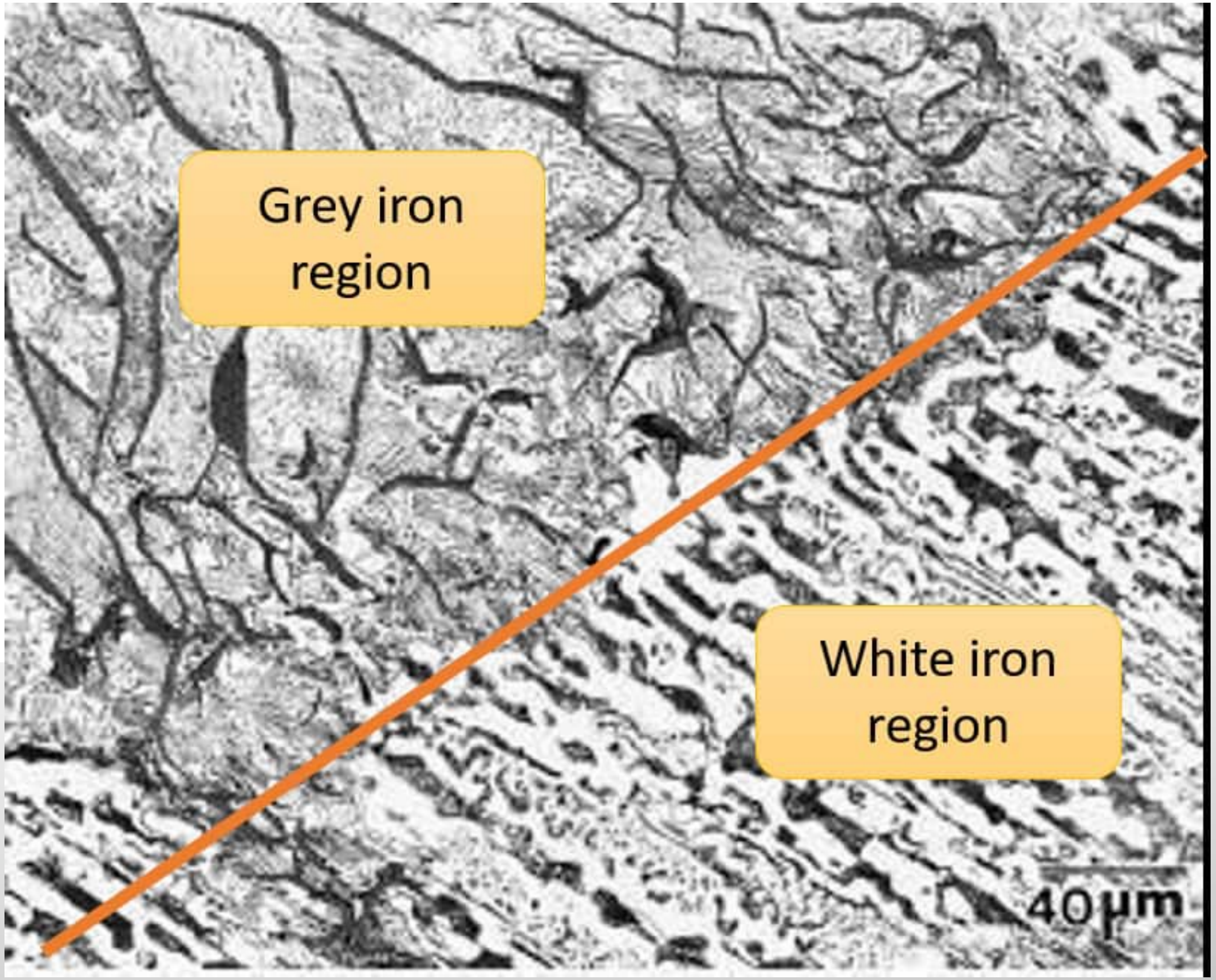
CAST IRONS

- Cast iron containing graphite (**graphitised cast iron**) = **grey cast iron**.
  - Graphitisation is favoured by slow cooling in the presence of silicon.

- **White cast iron** (owing to presence of cementite):
  - Extremely hard
  - Brittle
  - Excellent wear resistance properties to the surfaces of castings

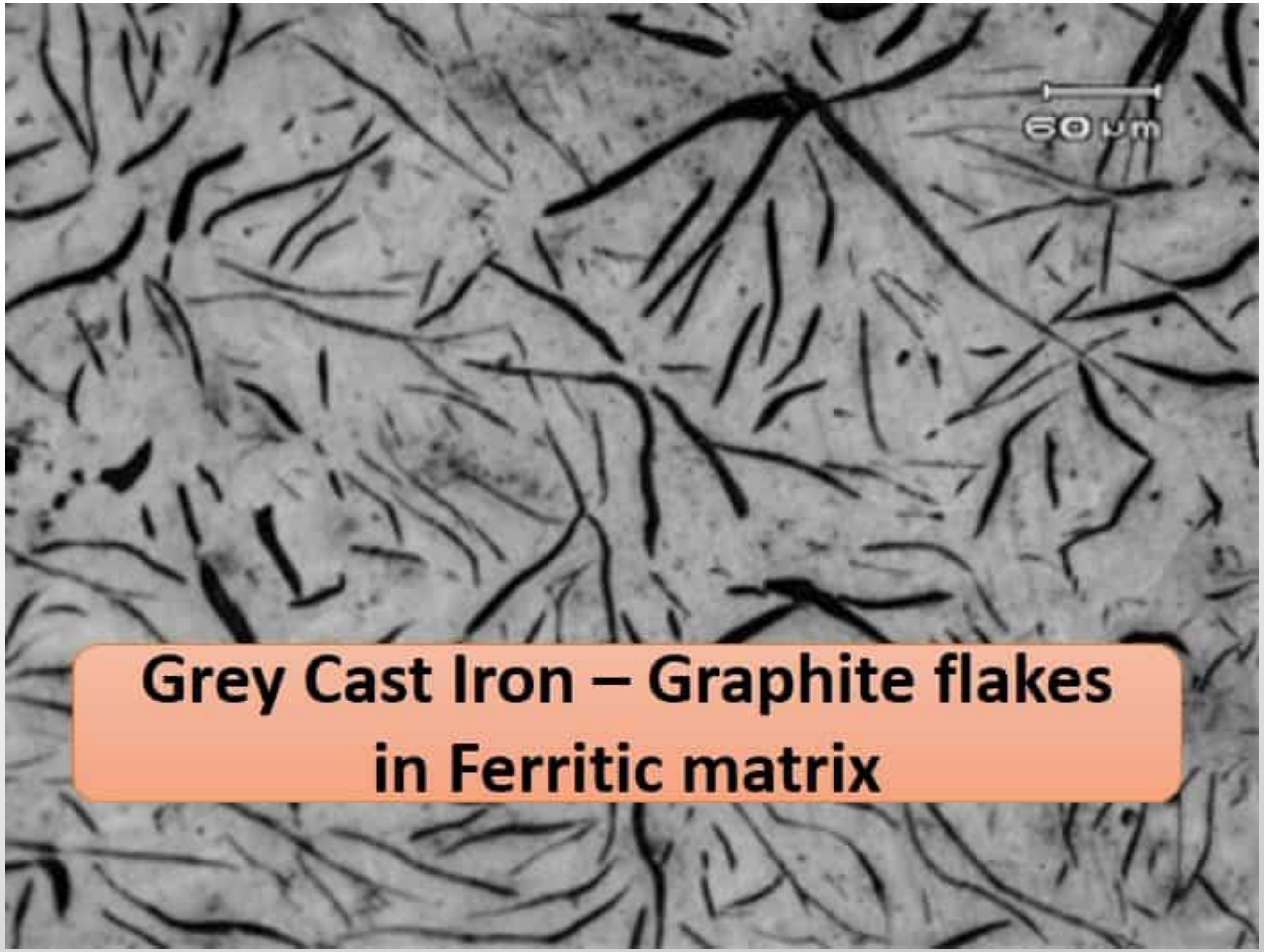
CAST IRONS

White Cast Iron



CAST IRONS

- **Grey cast iron**
  - Graphite is distributed in flakes which break up the continuity of the metal matrix.
  - **Ferrite grey cast iron**
    - All the carbon is graphite



CAST IRONS

- **Pearlitic grey cast iron**
  - There is some presence of pearlite
  - Graphite flakes have no strength and act as internal cracks
  - Therefore the material is weak and brittle.
  - Extremely liable to fracture under shock loads

Assignment 3:

Refer to the Iron-Carbon Phase Diagram. Consider alloys containing 0.5% C, 0.83% C and 1% C, which have been slowly cooled from the austenite region (say 1100^{o}C) to room temperature. Answer the following questions.

1. Why is slow cooling preferred to rapid cooling?
2. Describe the transformations that occur in the complete but slow cooling process of these alloys.
3. Calculate the relative amounts and compositions of the phases present at room temperature.
4. Draw the microstructure, which would result in each case.

Submit question 3 only as Assignment 3 (on Moodle).
This Assignment is Due in <u>One Week's Time</u>.

END OF LECTURE 9