MATERIALS ENGINEERING
MT30001
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Offered by:

Metallurgical & Materials Engineering Dept.

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Physical metallurgy of steels

Content of this course

- Iron-carbon diagram
- Study of phase transformations in steel
- Alloying elements in steel and hardenability
- Heat treatment of steels
- Some basic steels and cast irons

Textbooks referred to:

- Introduction to Physical Metallurgy – S. H. Avner
- Physical Metallurgy Principles and Design – G. N. Haidemenopoulus
- Materials Science and Engineering an Introduction – W. D. Callister
- Physical Metallurgy Principles – R. E. Reed-Hill
- Lecture notes – Technische Universität Graz

Majority of the images in this course have been collected from different textbooks and scientific documents available in internet. They are not from my own research and have been used solely here for teaching purpose

Technological importance of steel

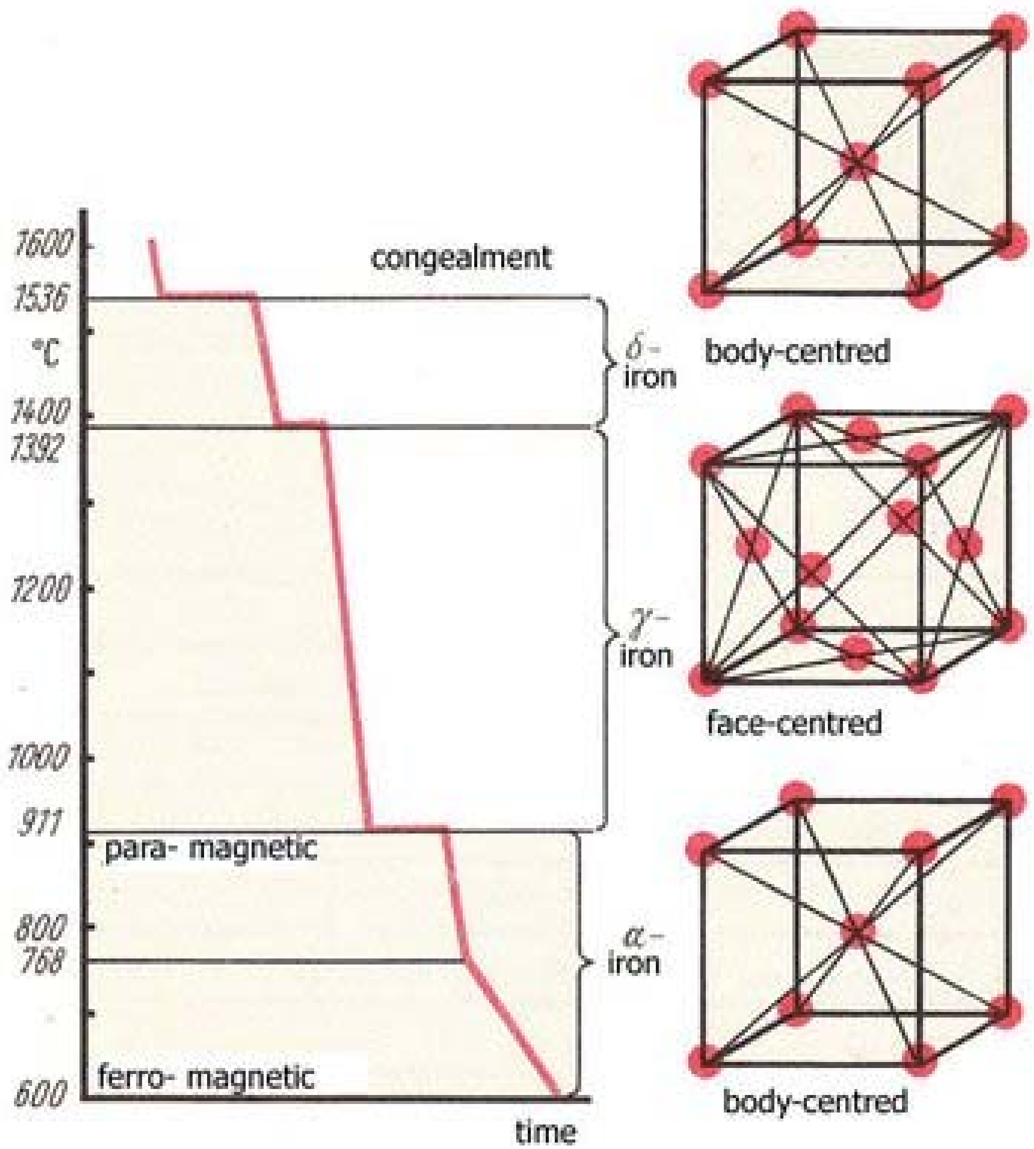
- Steel is the most important engineering material used by mankind
- Steels constitute > 80% of all industrial alloys
- Application of steel is extremely varied – home appliances - machine parts – automobiles – ships- buildings – bridges etc.
- Steel is low cost, easily manufacturable and recyclable
- Iron, the fundamental constituent of steels, is the fourth most abundant element in earth‘s crust

In spite of the advent of all modern materials, technologically we are still in the „Steel age“

What is steel

- Steel is essentially a solid solution of iron and carbon. The amount of carbon and the level and amount of impurities and different alloying elements in steel determine their pproperties.
- Carbon forms interstitial solid solution with iron
- Due to the allotropic nature of iron, it is present in different crystal structure forms at different temperatures

Allotropy of iron

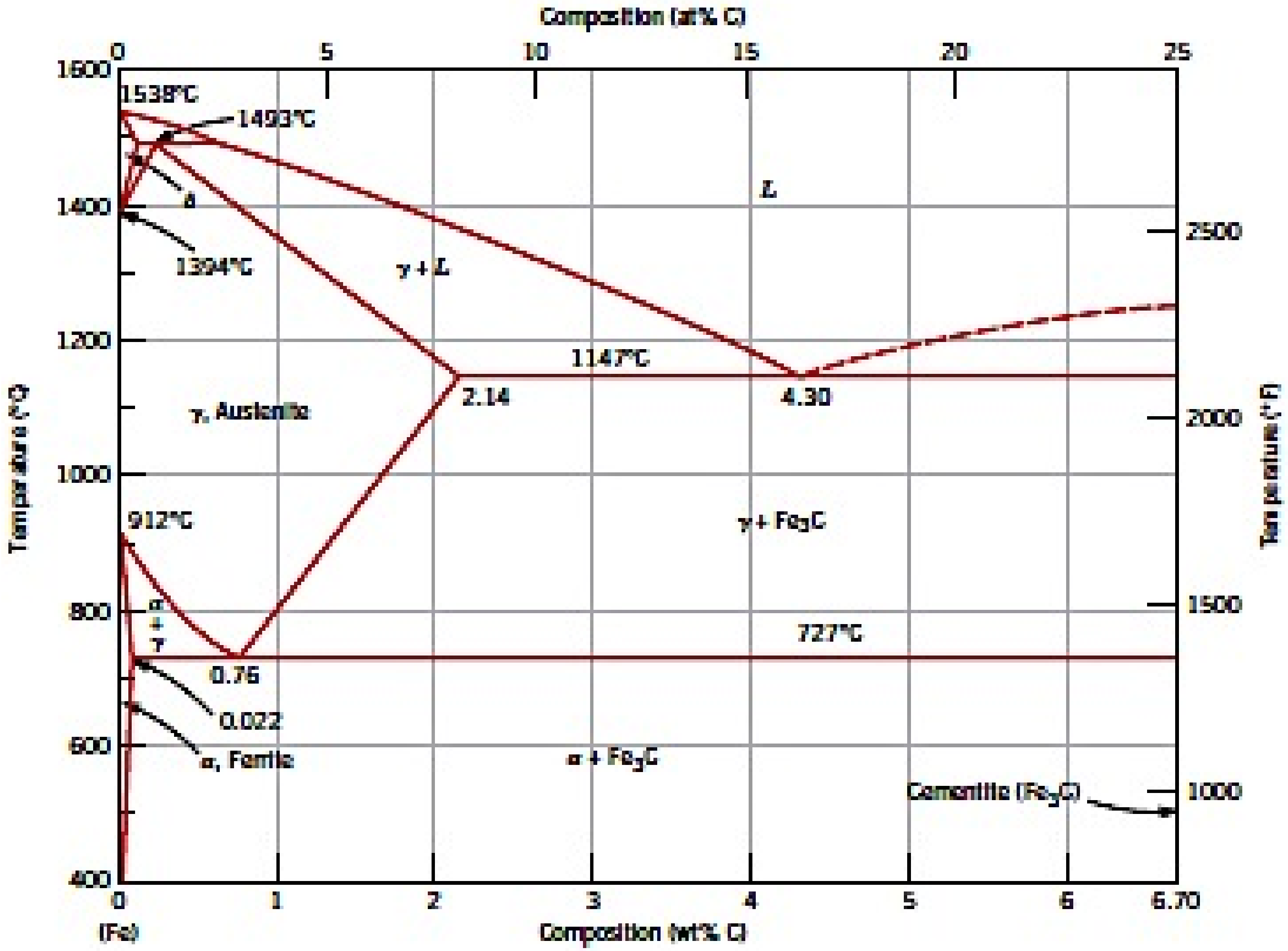


http://www.dierk-raabe.com/steels-science/

Allotropy of iron

- At room temperature the crystal structure of iron is bcc and it is magnetic in nature ➔ α-iron
- When α-iron is heated, at 768 °C iron becomes non-magnetic without changing the crystal structure ➔ β-iron
- At 911 °C the crystal structure changes from bcc to fcc ➔ γ-iron
- With continued heating, at 1392 °C the crystal structure reverts back to bcc ➔ this high temperature bcc form is called δ-iron
- Finally pure iron melts at 1536 °C

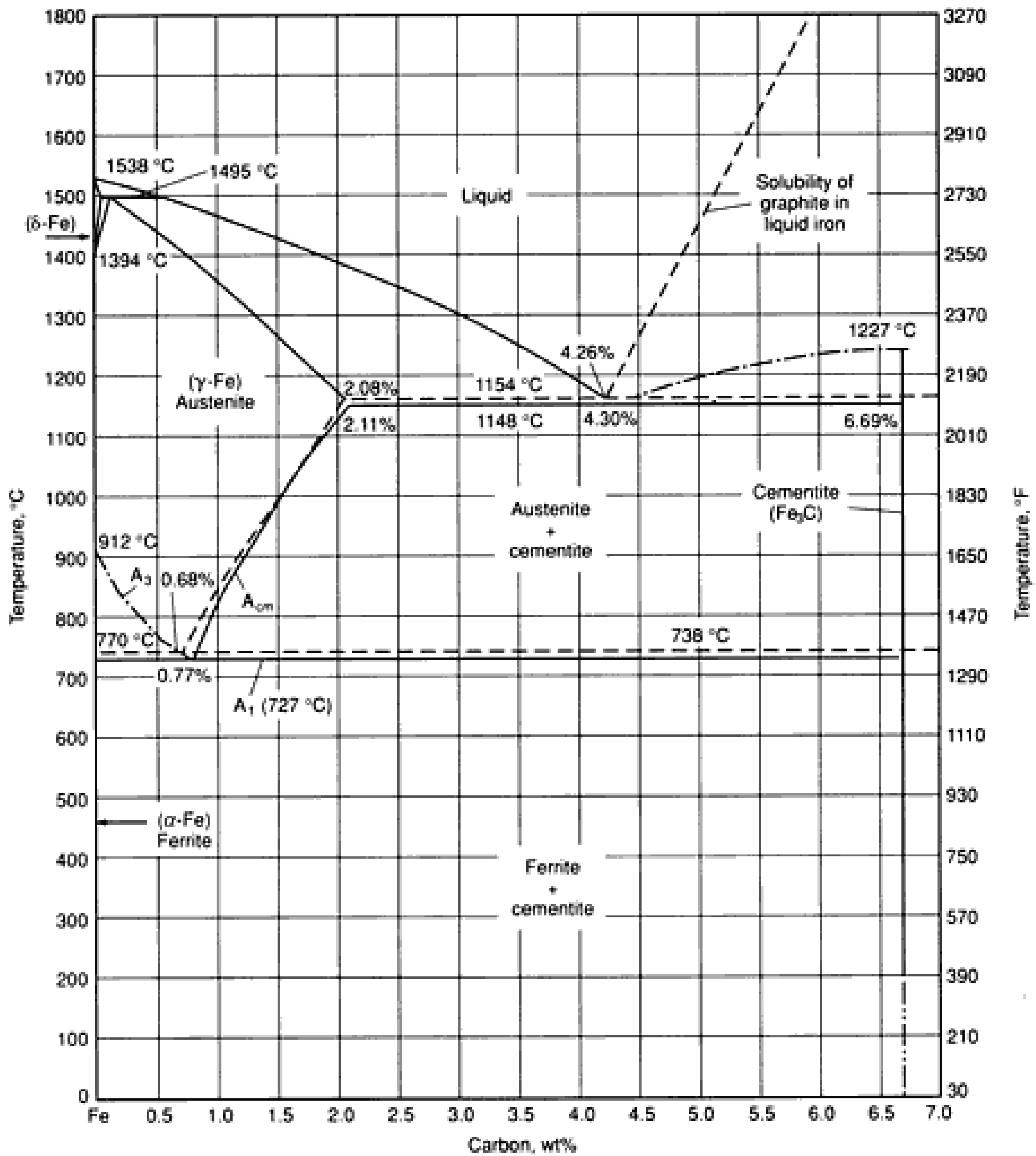
Metastable Fe-Fe_3C phase diagram



Metastable Fe-C phase diagram

- The phase diagram is not a complete one as it is only plotted upto 6.70 wt.% C ➔ the composition of Fe_3C
- Part of the diagram with C-content > 6.70 wt.% C is of little significance and is generally ignored.
- It is not a true equilibrium diagram, as Fe_3C is not a truly equilibrium phase
- Given sufficient time (several years even at 700 °C), Fe_3C will decompose to form graphite, which is an equilibrium phase
- Fe_3C is called a metastable phase and the $Fe\text{-}Fe_3C$ phase diagram is called a metastable phase diagram.

Equilibrium Fe-C phase diagram

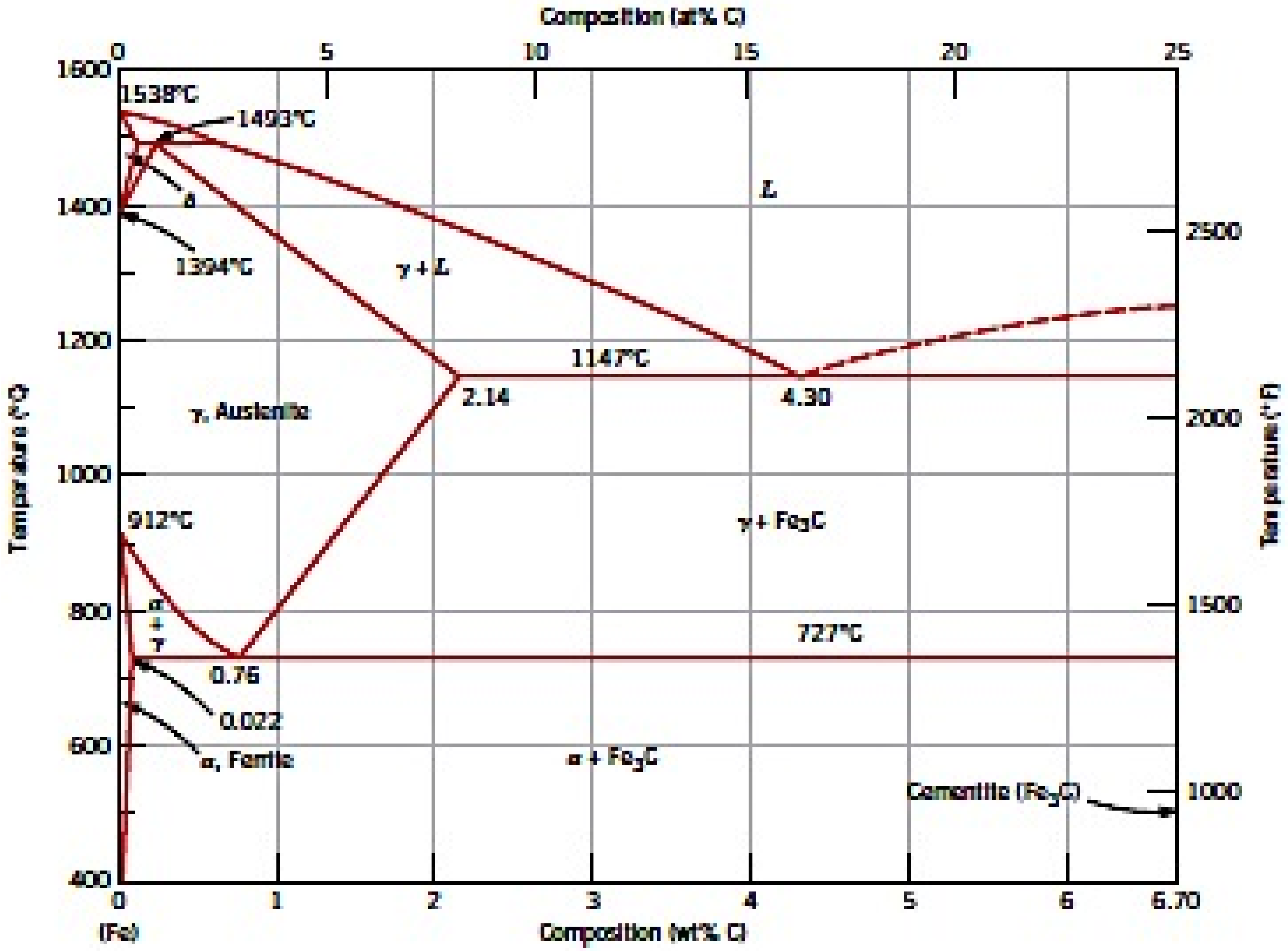


Equilibrium Fe-C phase diagram

- The dotted lines correspond to the equilibrium Fe-C diagram, while the solid lines denote the metastable Fe-Fe_3C diagram
- The difference between the two diagrams is small, except in the region of the eutectic reaction
- As the equilibrium phase diagram is valid at ulrealistic time scales, the metastable phase diagram is considered as equilibrium diagram for all practical purposes

The discussion in this course will be limited to the metastable phase diagram, if not specifically mentioned

Metastable Fe-Fe_3C phase diagram



Invariant reactions

Three invariant reactions are occurring in this phase diagram

1) Peritectic reaction at 1493 °C

$$L(0.51\%C) + \delta(0.11\%C) \rightarrow \gamma(0.16\%C)$$

2) Eutectic reaction at 1147 °C

$$L(4.30\%C) \rightarrow \gamma(2.14\%C) + Fe_3C$$

2) Eutectoid reaction at 727 °C

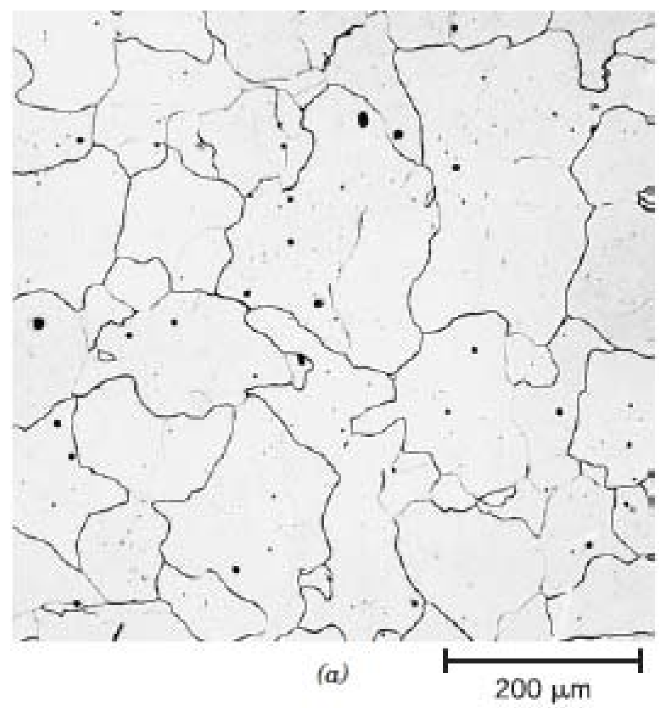
$$\gamma(0.76\%C) \rightarrow \alpha(0.025\%C) + Fe_3C$$

Phases in Fe-Fe_3C diagram

α-Ferrite

- Low temperature form
- Interstitial solid solution of carbon in bcc iron
- Due to the small size of the interstitial sites in bcc lattice, the solubility of C in α-ferrite is very low (max. 0.025 wt.% at 727 °C and 0.008 wt.% at room temperature)
- It is relatively soft and ductile

Optical micrograph of ferrite

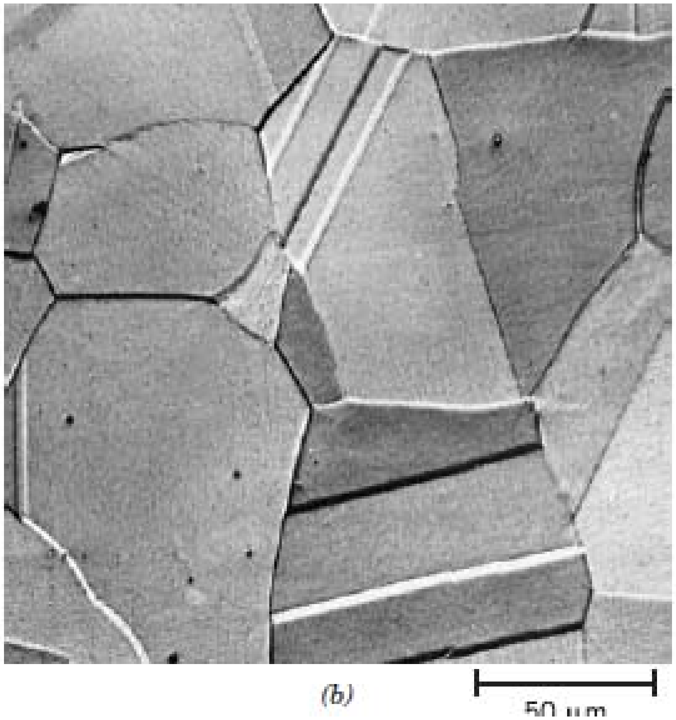


Phases in Fe-Fe_3C diagram

Austenite

- Interstitial solid solution of carbon in fcc iron
- Due to the larger size of the interstitial sites in fcc lattice, the solubility of C in austenite is significantly higher (max. 2.14 wt.% at 1147 °C)
- It is non-magnetic, relatively soft and ductile

Optical micrograph of austenite



Phases in $Fe\text{-}Fe_3C$ diagram

Cementite

- Cementite is an intermediate compound of iron and carbon with 6.70 wt.% C and chemical formula Fe_3C
- It has orthorhombic crystal structure
- Cementite is metastable in nature and at room temperature it remains as a compound for an indefinite period
- It is extremely hard and brittle

Phases in Fe-Fe_3C diagram

δ-ferrite

- It is virtually the same as α-ferrite; however it is stable at very high temperatures (> 1400 °C)
- It is of no technological importance

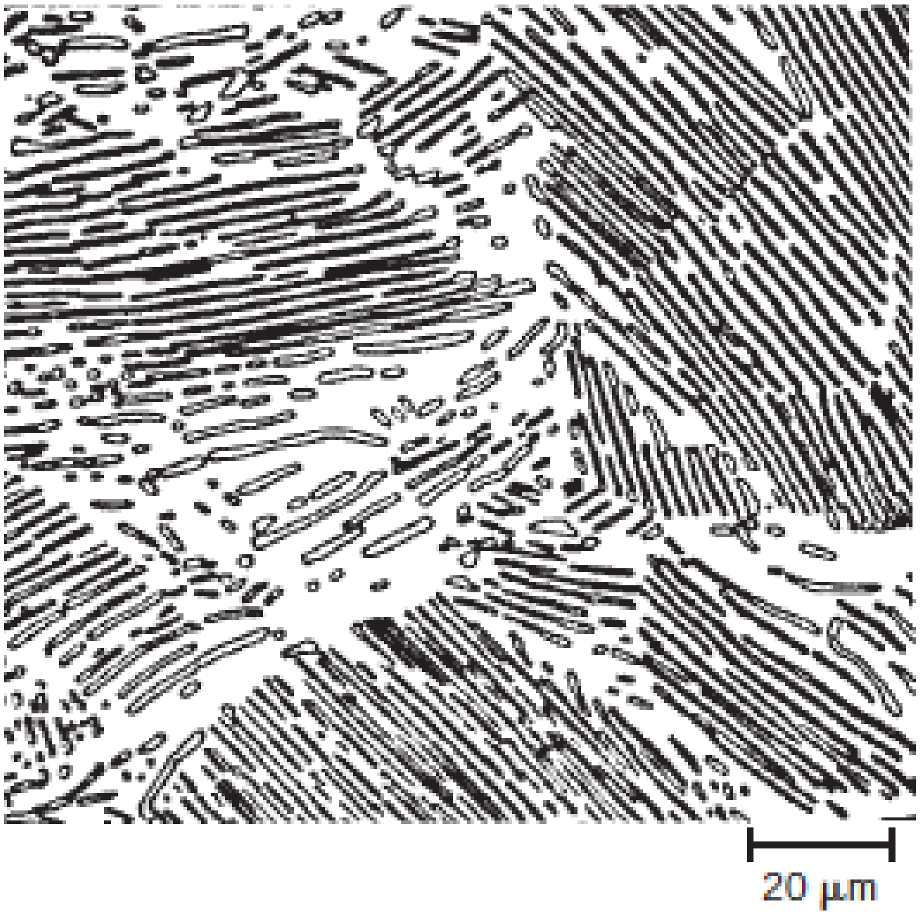
Phases in Fe-Fe_3C diagram

Pearlite

- It is eutectoid mixture of α-ferrite and cementite.
- It consists of alternating layers or lamellae of the phases ferrite and cementite
- Pearlite exists as colonies - within each colony the lamellae are essentially parallel; the orientation in each colony is different
- The mechanical properties of pearlite are intermediate between the soft, ductile ferrite and hard, brittle cementite.

Phases in Fe-Fe_3C diagram

Pearlite



Photomicrograph of pearlite. Cementite lamella are dark while the ferrite lamella are brighter

Ferrous alloy classification based on C-content

- Commercially pure iron: C-content < 0.008 wt.%
- Steel: 0.008 wt.% < C-content < 2.14 wt.%
- Cast irons: 2.14 wt.% < C-content < 6.70 wt.%

Eutectoid steel

Steel containing exactly 0.76 wt.% C

Hypoeutectoid steel

Steel containing < 0.76 wt.% C

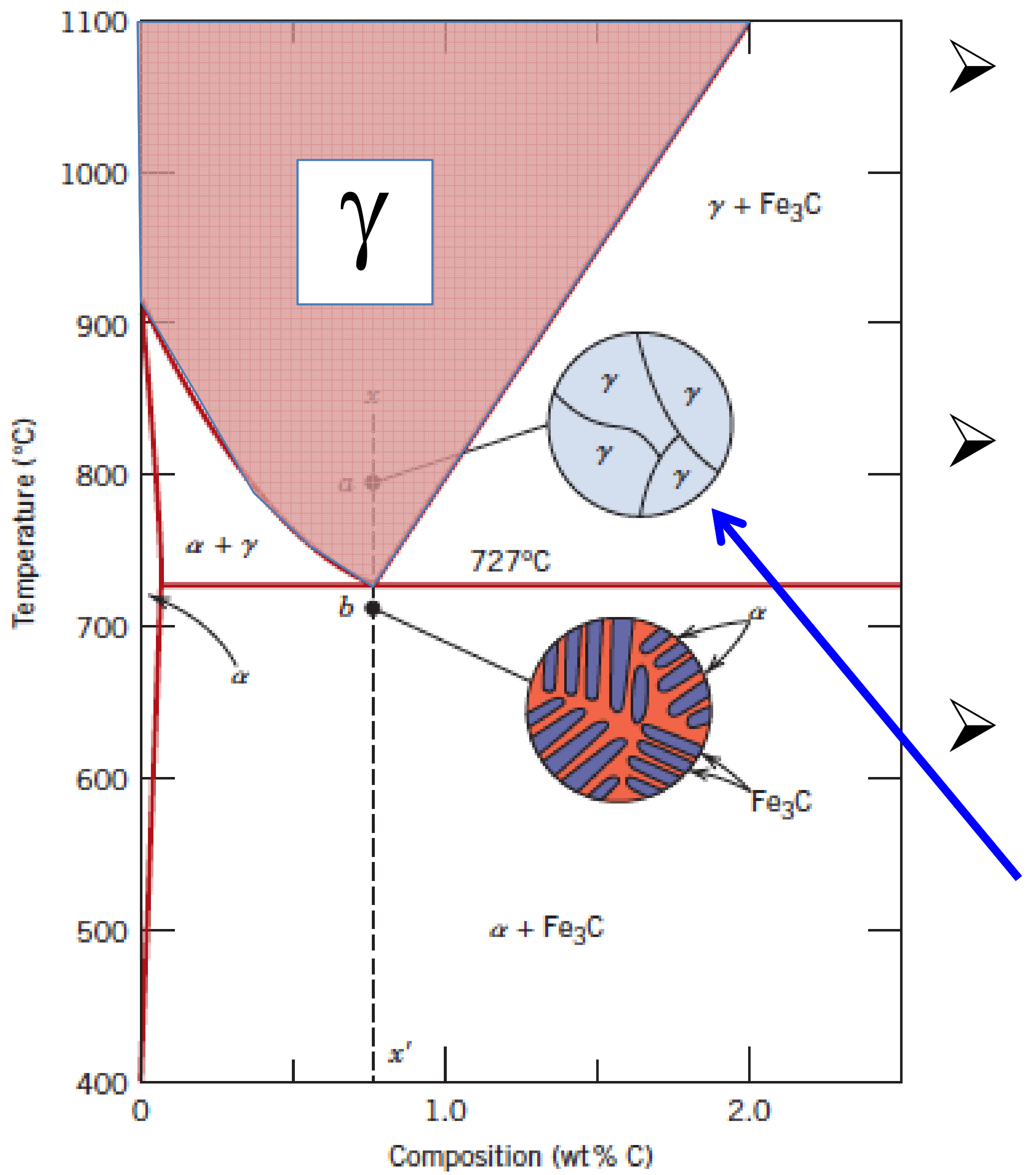
Hypereutectoid steel

Steel containing > 0.76 wt.% C

Microstructure development during slow cooling of steel

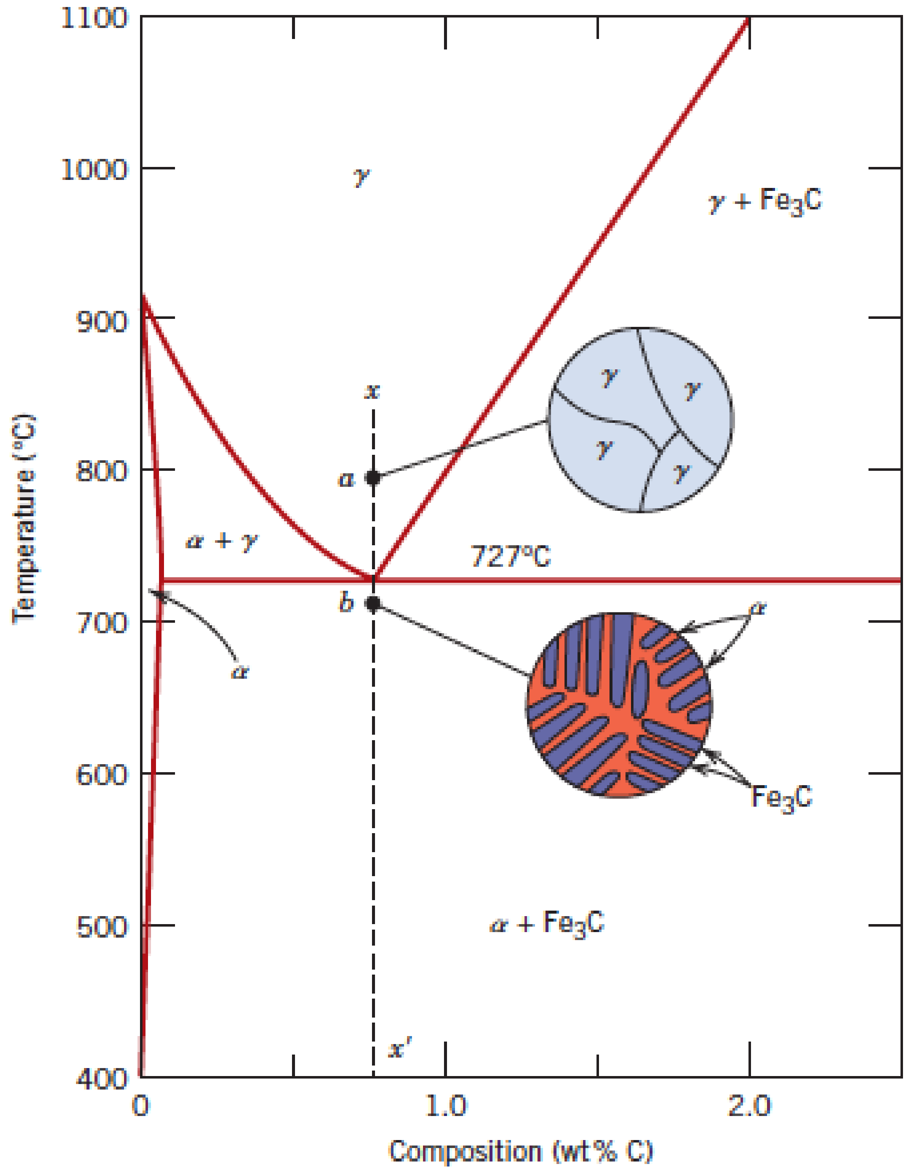
- The following discussion is valid for very slow cooling of steel where equilibrium is continuously maintained
- The following cases will be discussed separately
  - Steel having etectoid composition
  - Steel having hypoeutectoid composition
  - Steel having hypereutectoid composition

Eutectoid composition



- The eutectoid composition is denoted by the vertical line xx‘ at a C-content of 0.76 wt.%
- Cooling starts from the single phase austenitic region (marked with γ)
- Initially the alloy consists of 100% austenite and the corresponding microstructure is shown schematically

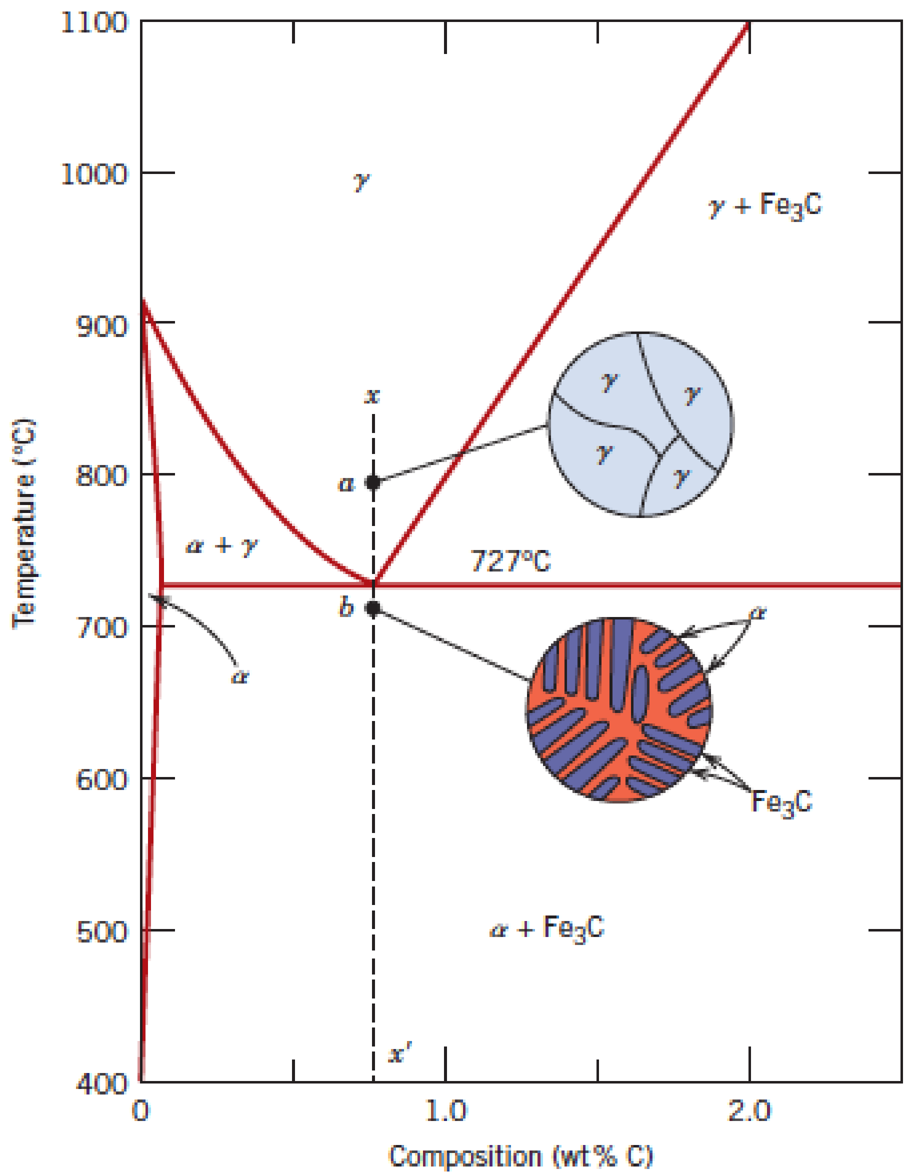
Eutectoid composition



- Upon cooling, no changes will occur until the eutectoid temperature of 727 °C is reached
- Upon crossing the eutectoid temperature, austenite transforms according to the equation:

$$\gamma \rightarrow \alpha + Fe_3C$$

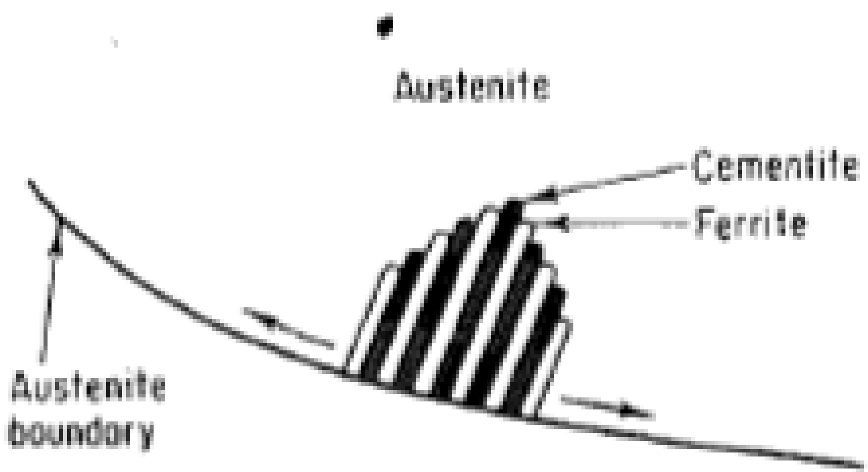
Eutectoid composition



- The microstructure consists of alternating layers of lamellae of the two phases α and Fe_3C.
- The microstructure is called pearlite.
- Further cooling to room temperature causes no significant change in microstructure.

Mechanism of pearlite formation

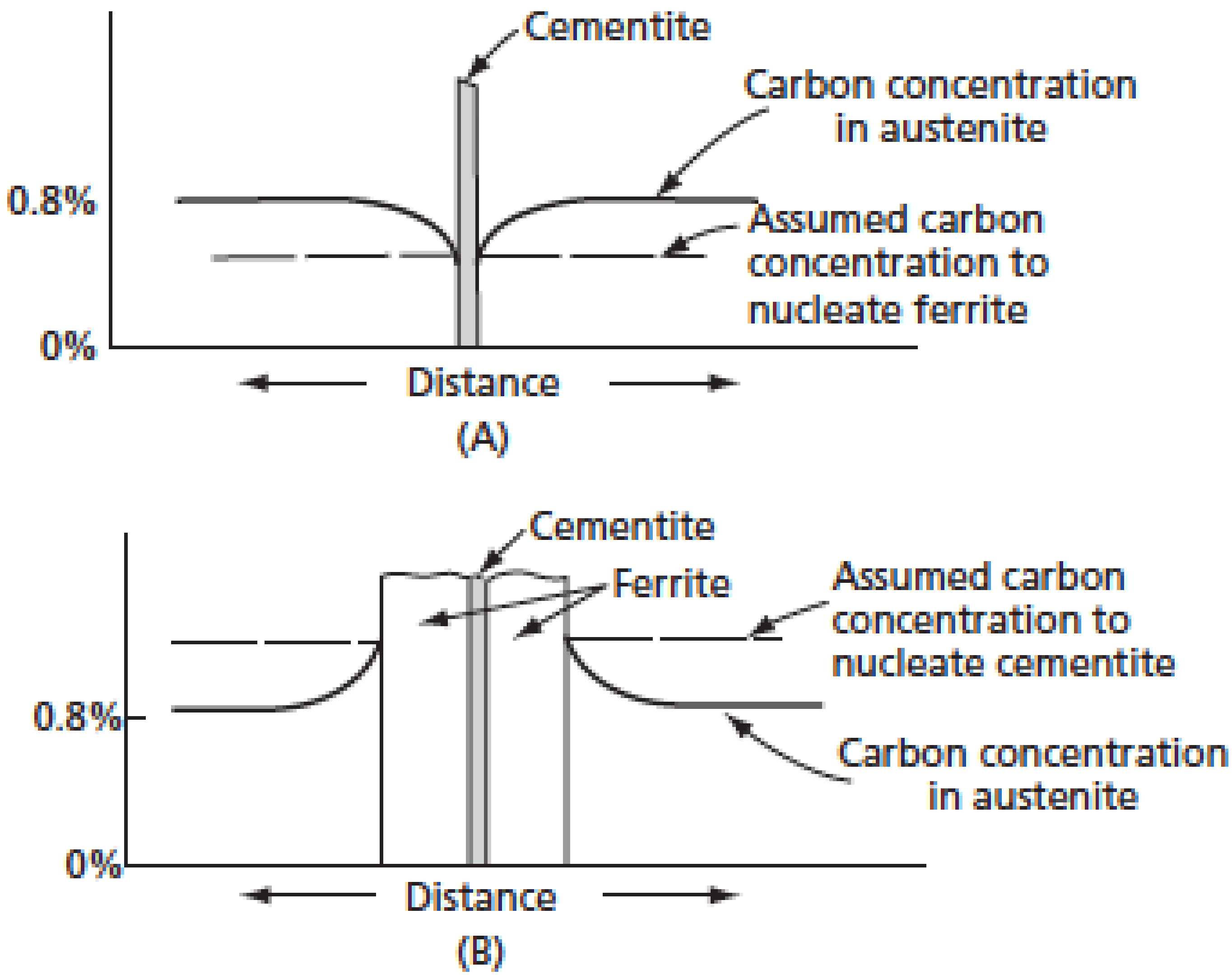
- The decomposition of austenite to form pearlite occurs by nucleation and growth
- The phase transformation requires that there be a redistribution of carbon in austenite by diffusion
- The reaction usually starts at an austenite grain boundary, with the pearlite growing along the boundary and into the grain.



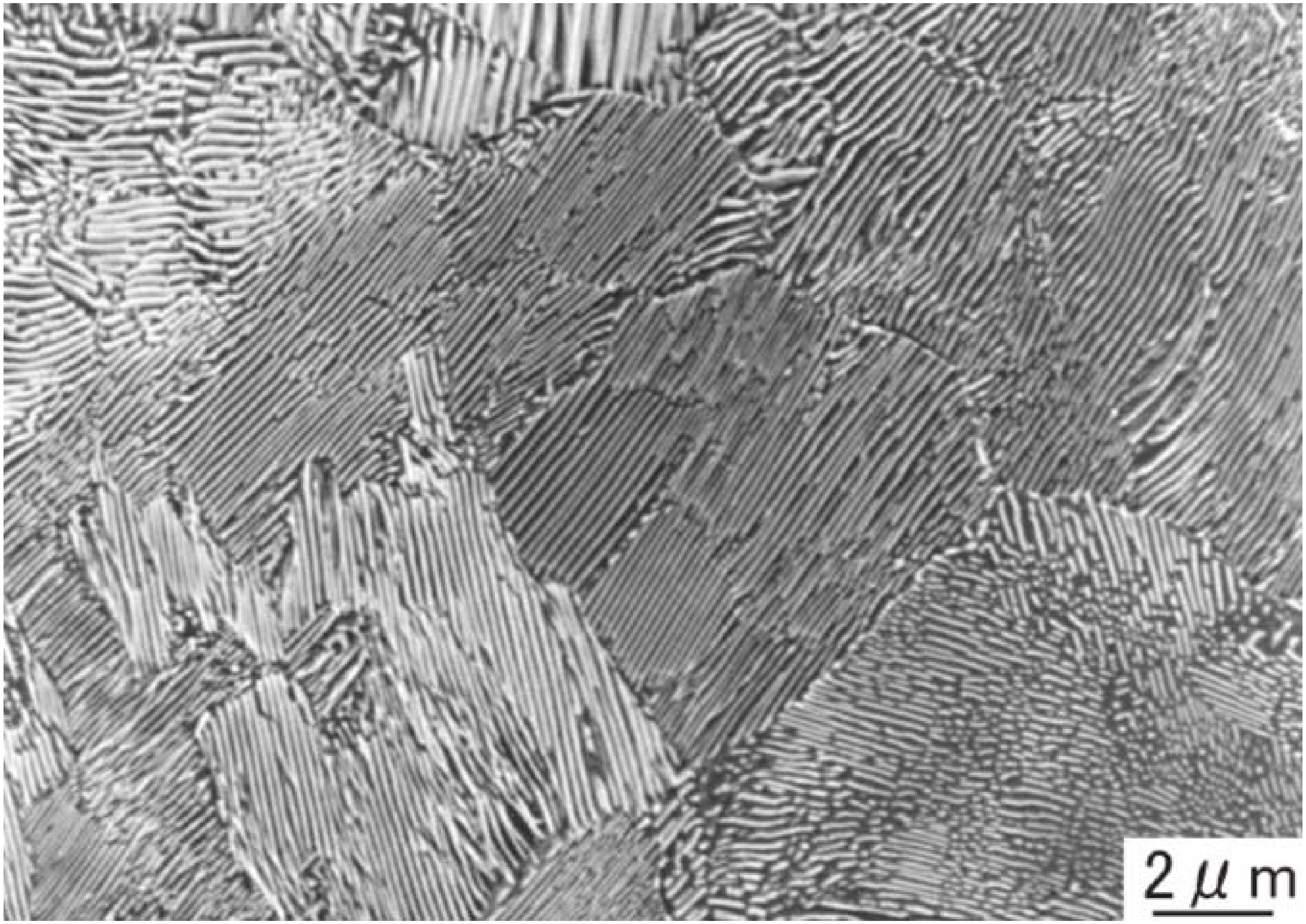
Mechanism of pearlite formation

- The transformation of austenite to form pearlite starts with the precipittion of carbon to form plates of cementite
- Consequently, the carbon concentration of the austenite next to the cementite lamella is reduced and promotes nucleation of ferrite
- The process is repetitive, so that as the colony grows, both the length and number of lamella increase
- Pearlite colonies grow unimpeded until they impinge on adjacent colonies

Mechanism of pearlite formation

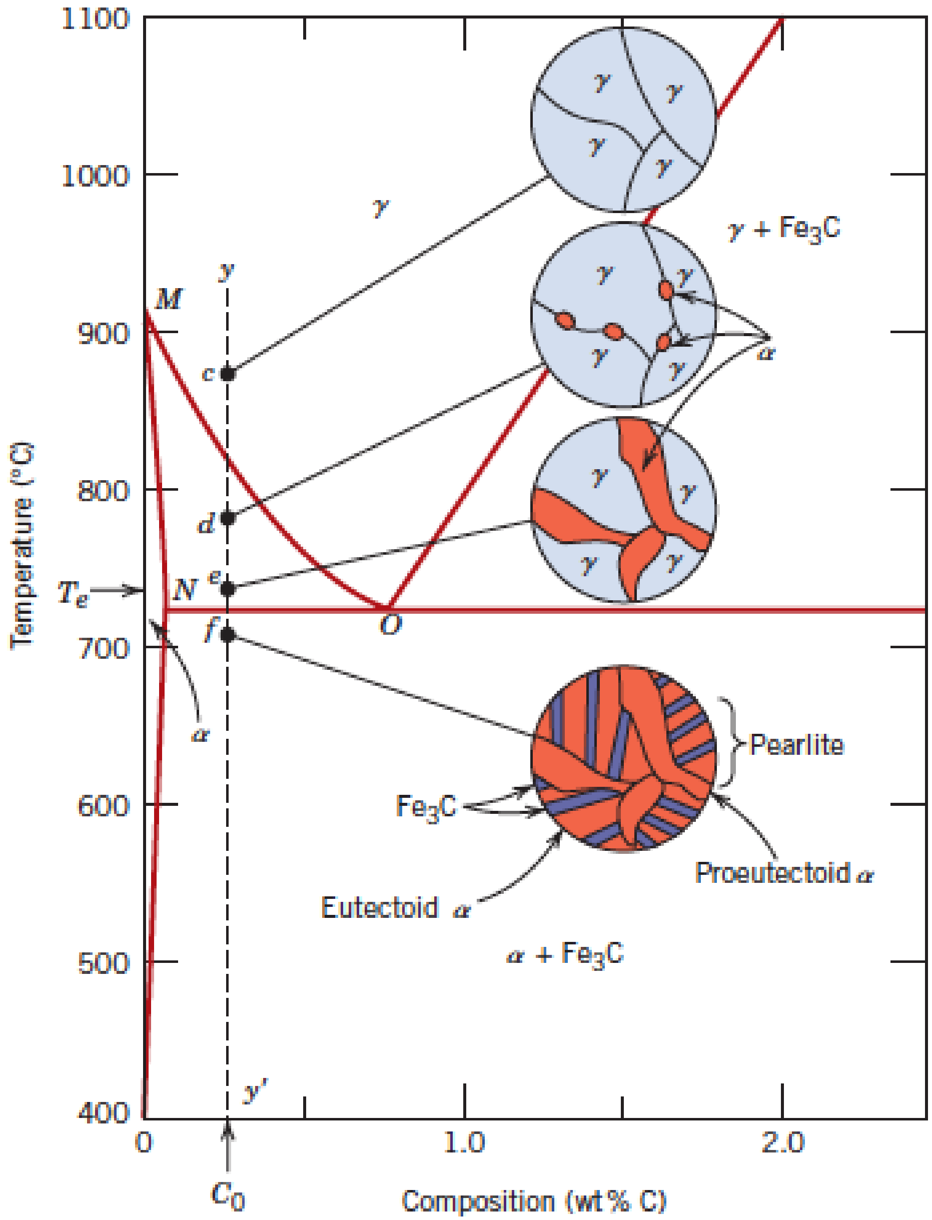


Eutectoid steel microstructure



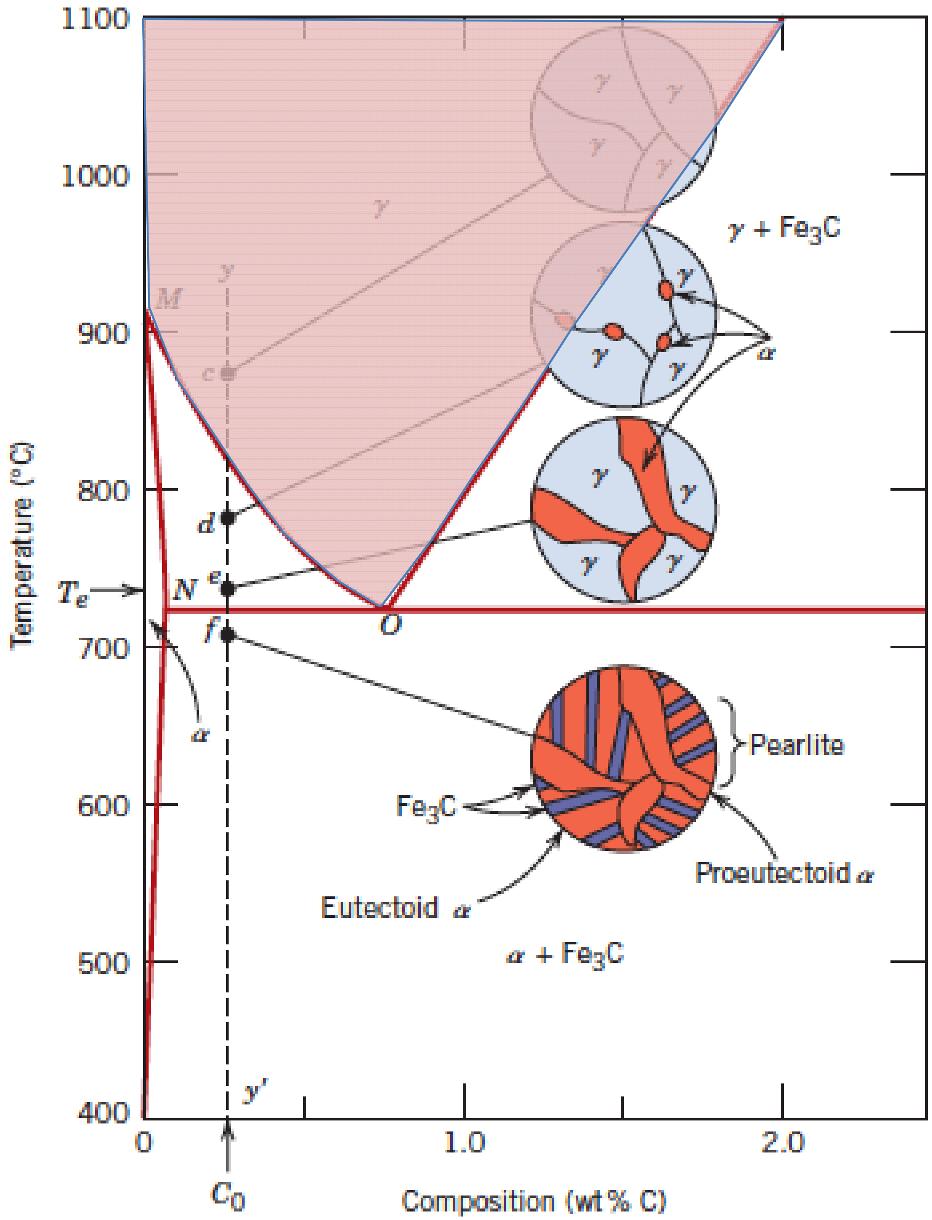
https://www.phase-trans.msm.cam.ac.uk/2008/Steel_Microstructure/SM.html

Hypoeutectoid composition

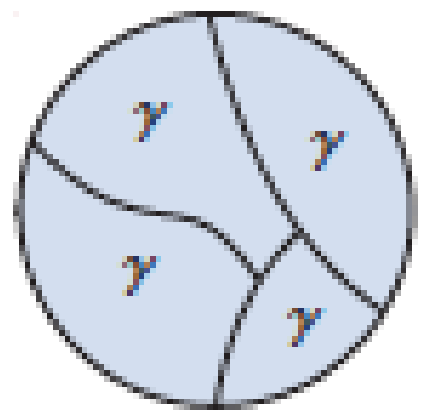


- The hypoeutectoid region corresponds to the left of the eutectoid composition, between 0.025 wt.% and 0.76 wt.% C.
- In the diagram this is denoted by the vertical line yy' at a C-content of c_0.

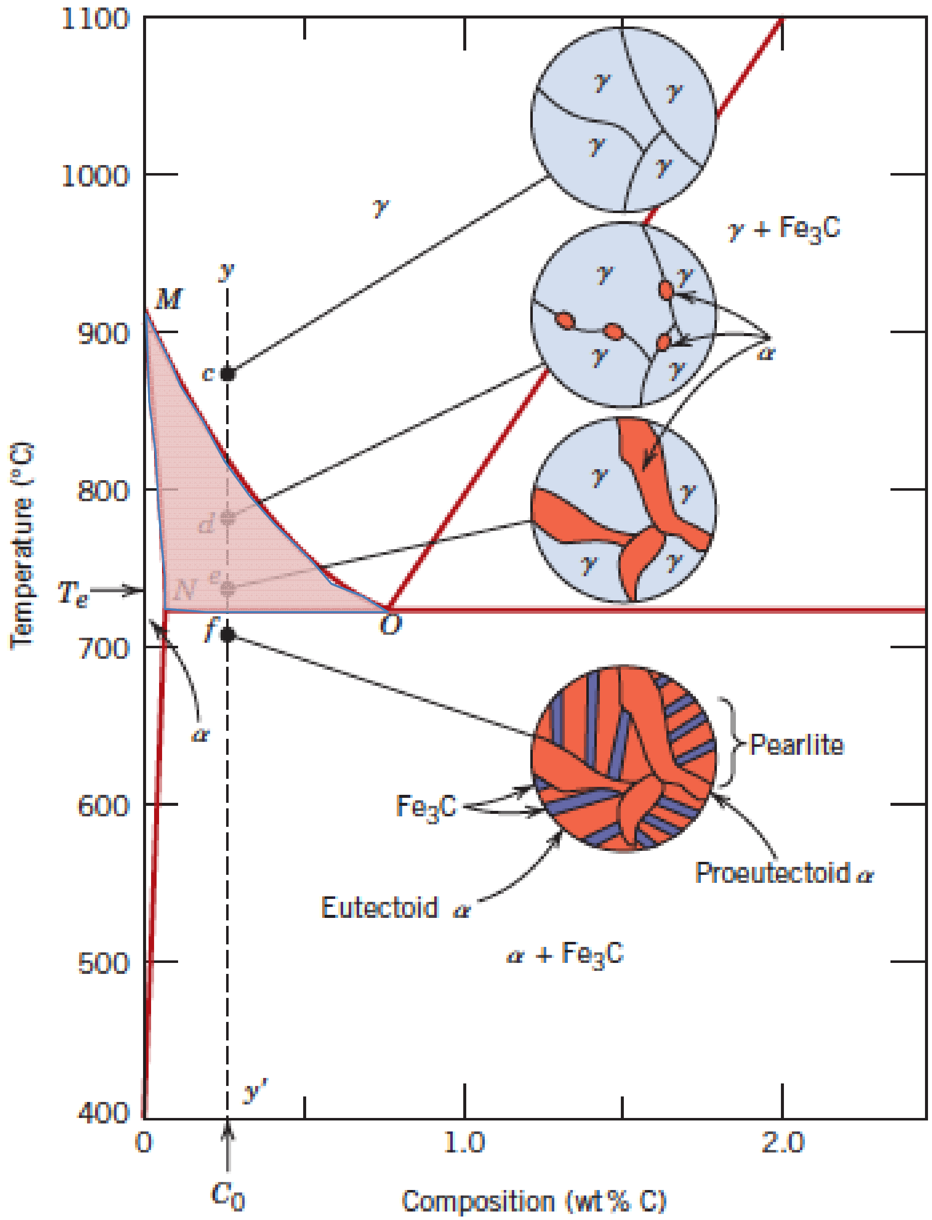
Hypoeutectoid composition



- At point c, in the austenite region, the microstructure solely consists of grains of single phase austenite.

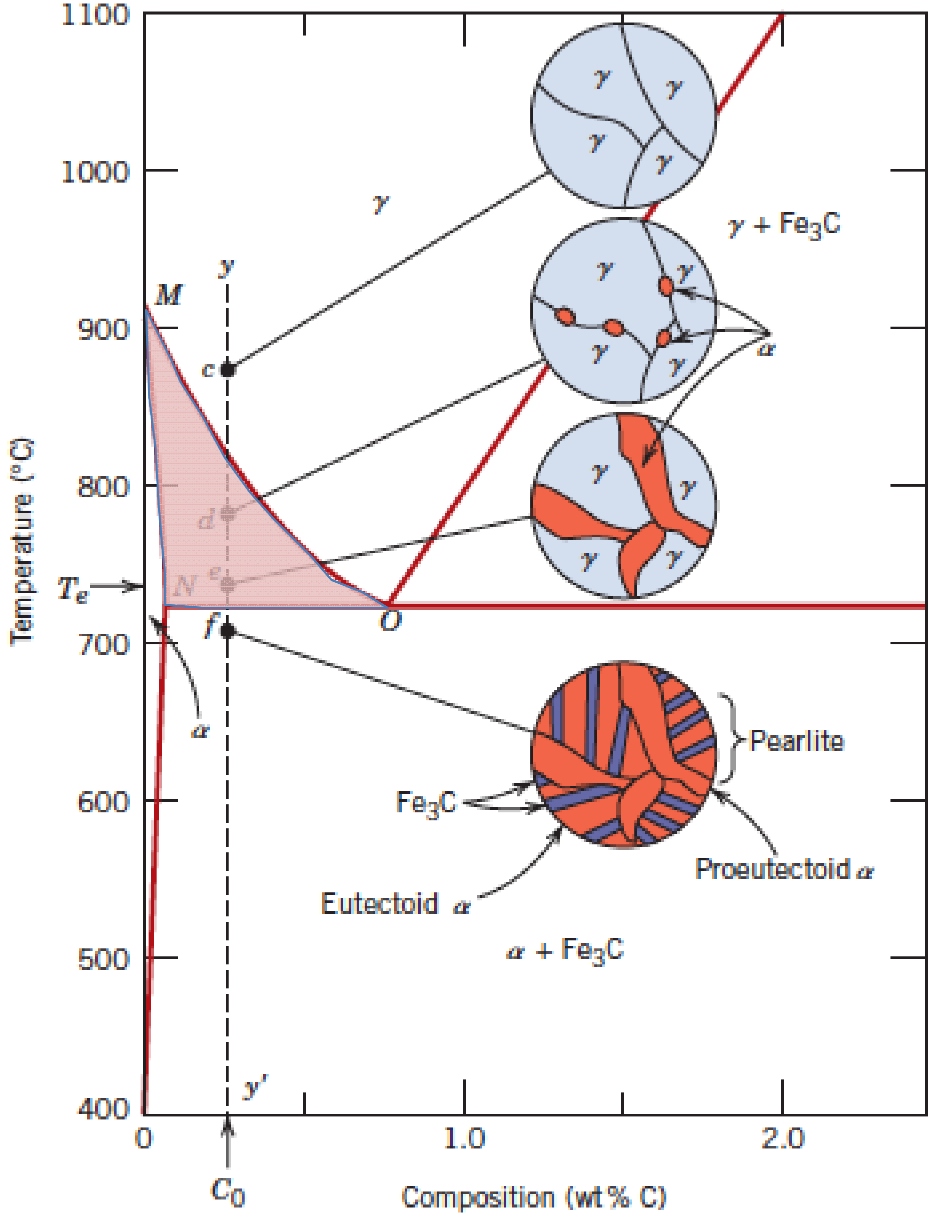


Hypoeutectoid composition



- Upon slow cooling nothing happens until the line MO is crossed
- As this line is crossed with further cooling, ferrite begins to form at the prior austenite grain boundaries.
- This ferrite is known as proeutectoid (i.e. pre- or before eutectoid) ferrite.

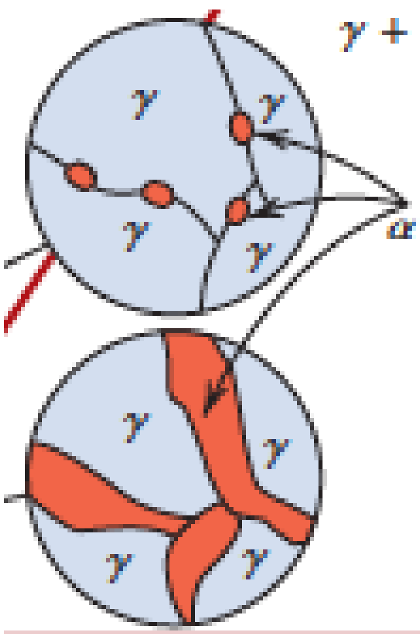
Hypoeutectoid composition



- Upon further cooling, the C-content in the ferrite follows the line MN.
- The C-content of austenite follows the line MO
- With increasing ferrite formation, due to its low C-content, the remaining austenite gets enriched with C

Hypoeutectoid composition

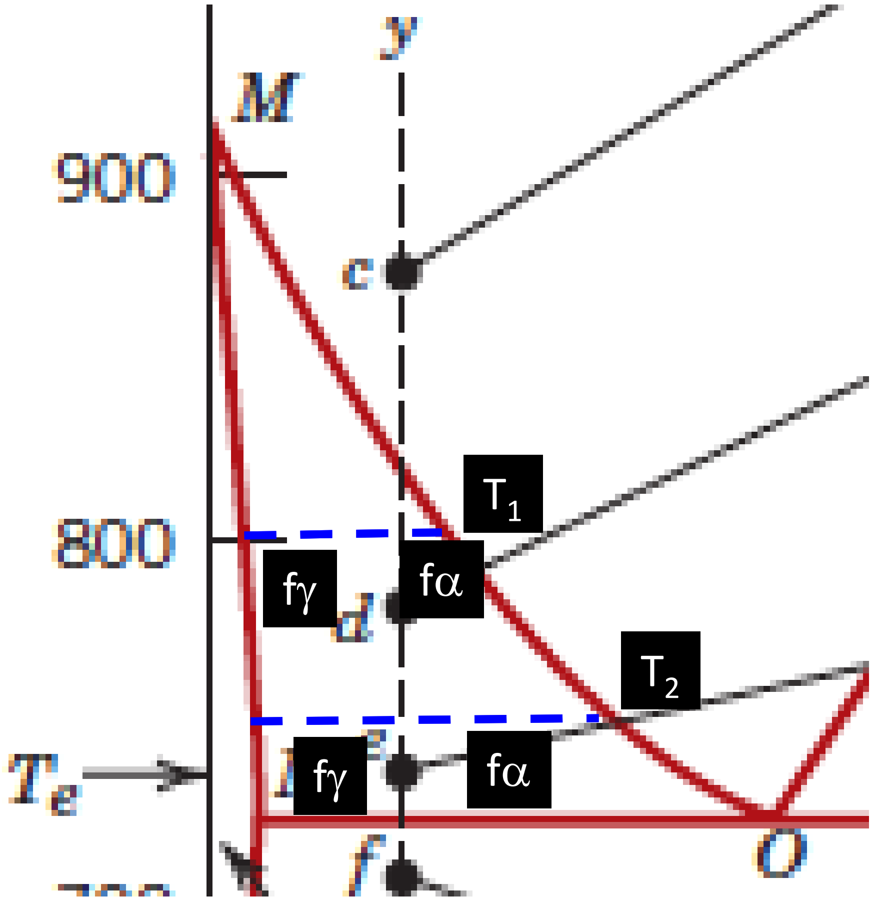
- With continued cooling in the two phase region, the amount of proeutectoid ferrite continuously increases and the earlier formed ferrite regions will become larger
- The relative amount of ferrite and austenite at any temperature in this two phase region can be determined from „lever rule"



Schematic microstructure at higher temperature

Schematic microstructure at lower temperature

Hypoeutectoid composition

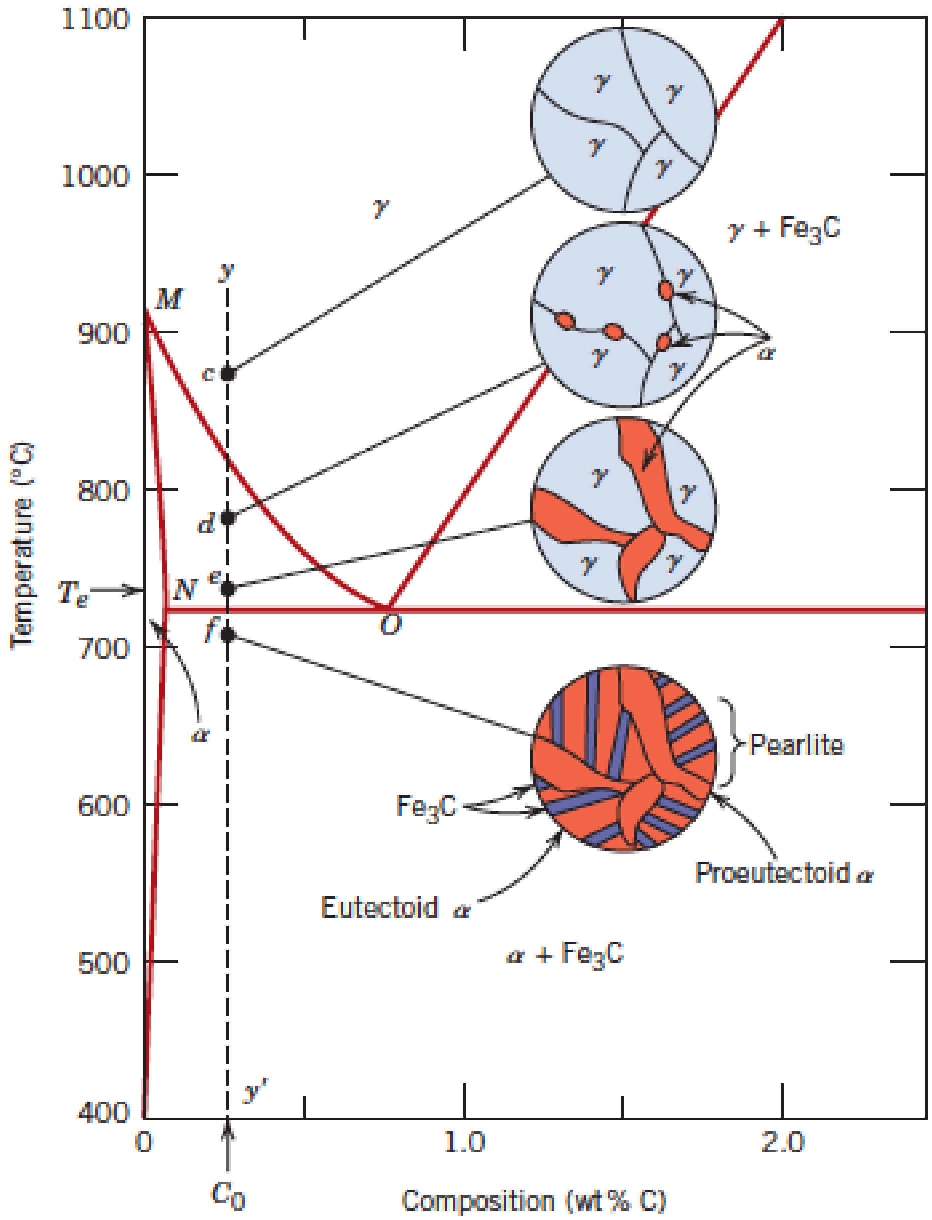


Lever rule

At any temperature, the fraction of ferrite (W_α) can be calculated as:

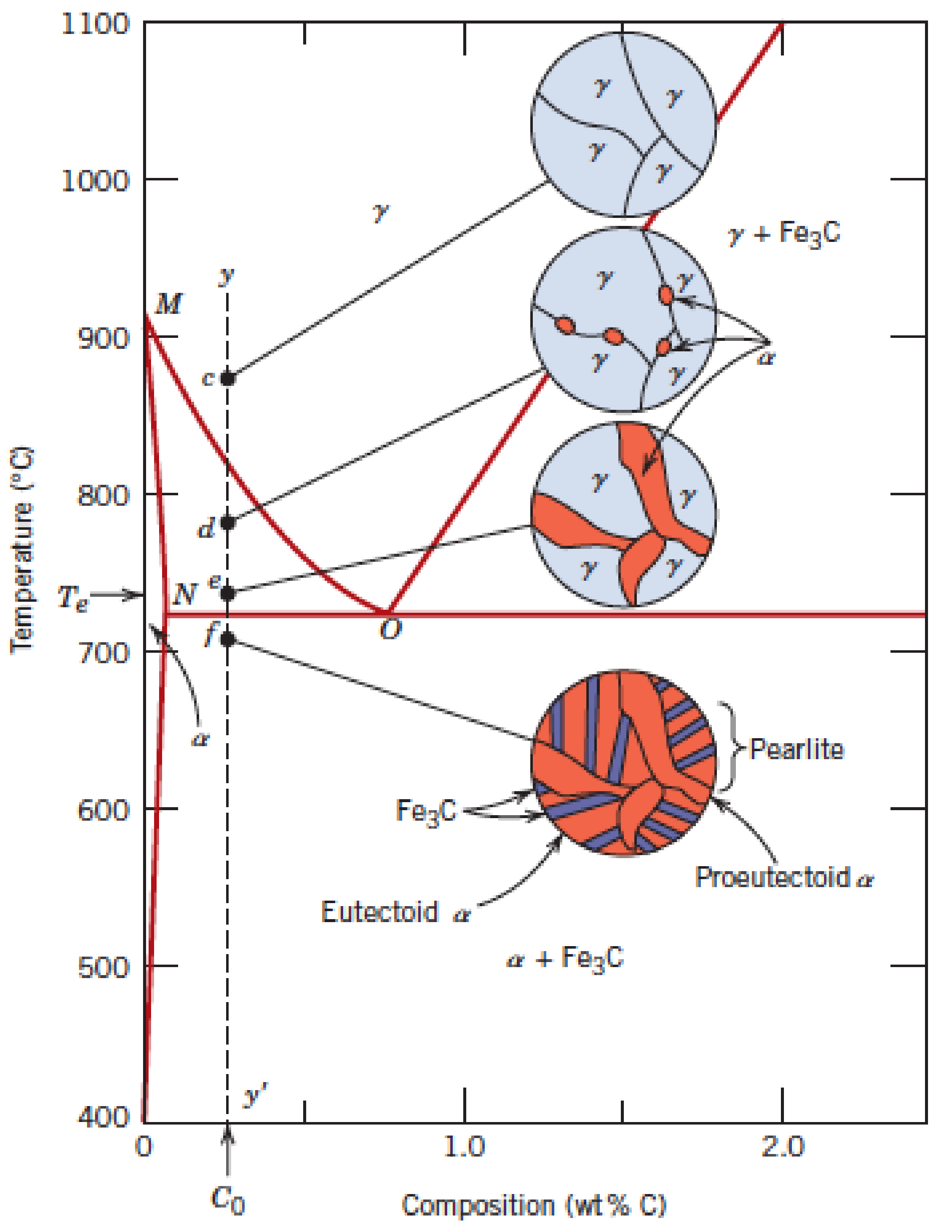
$$W_\alpha = \frac{f\alpha}{f\alpha + f\gamma}$$

Hypoeutectoid composition



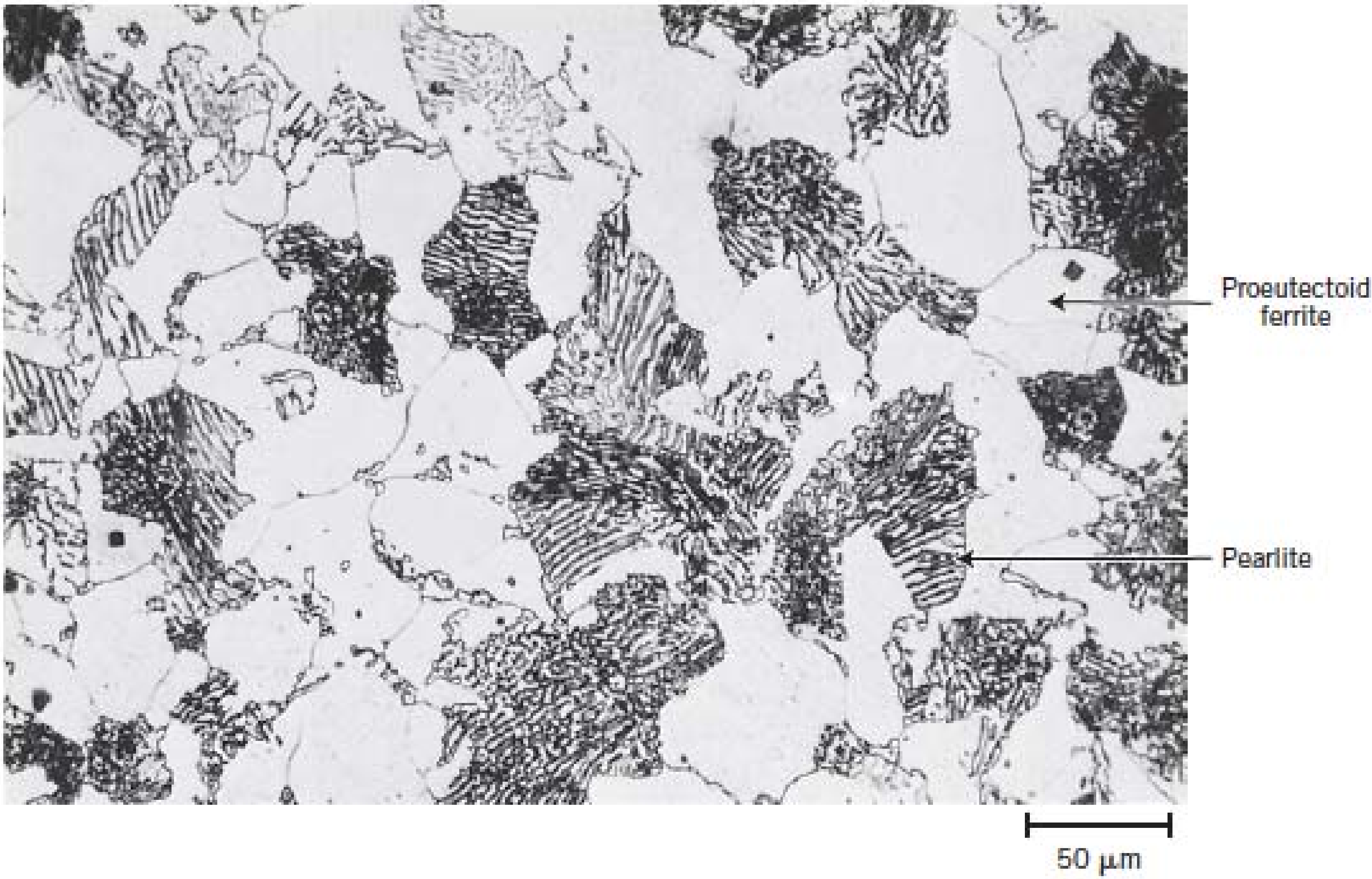
- As the temperature is cooled to just below the eutectoid temperature, all the γ phase will undergo eutectoid transformation and convert to pearlite (alternating lamella of ferrite and cementite)

Hypoeutectoid composition



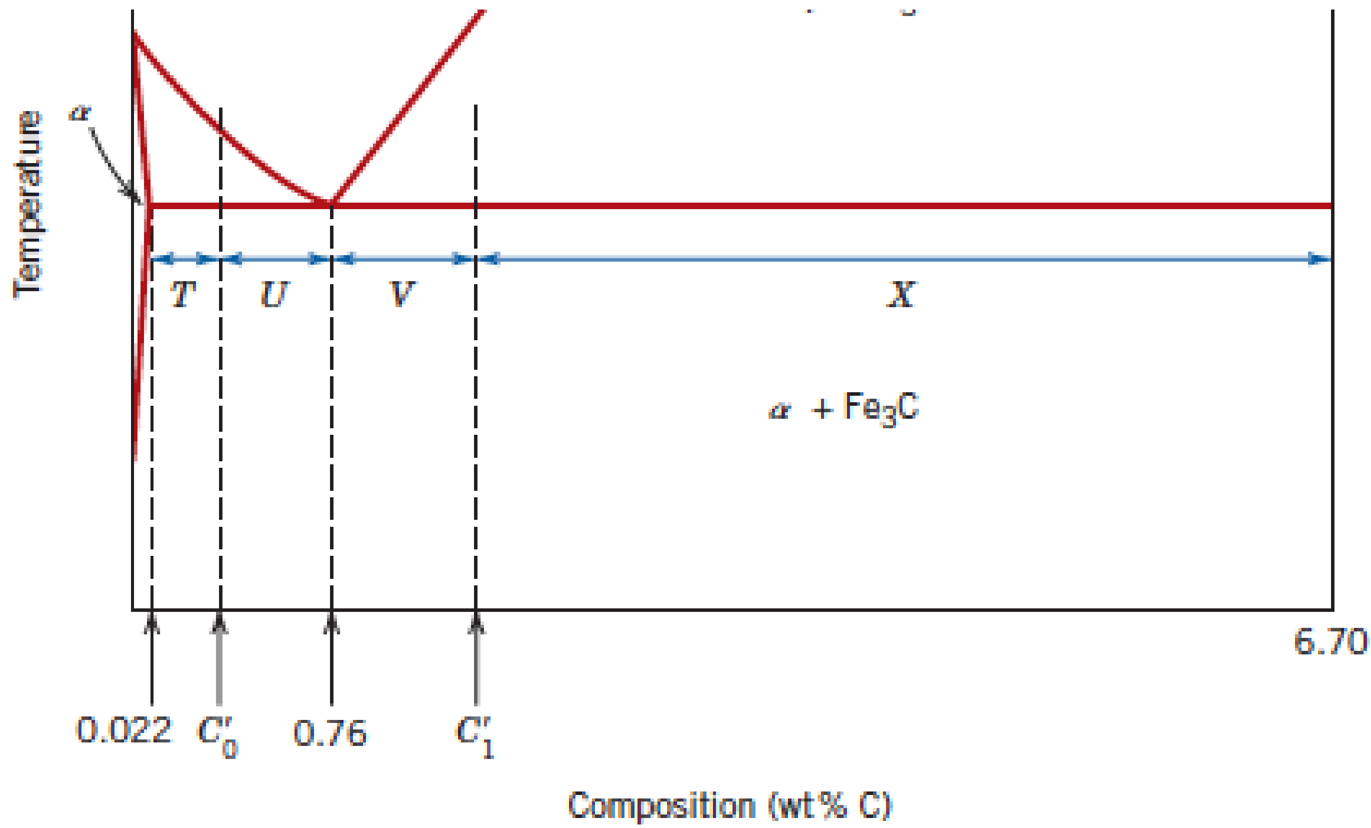
- Virtually no change occurs in the proeutectoid ferrite phase, which existed until the eutectoid temperature
- Proeutectoid ferrite exists as a continuous matrix phase surrounding the isolated pearlite colonies.

Hypoeutectoid steel microstructure



Estimation of phase amounts

Lever rule can be applied to the two phase region below the eutectoid temperature to determine the relative amounts of ferrite, cementite and pearlite



Estimation of phase amounts

Assuming a proeutectoid steel with a carbon content corresponding to $C_0^{'}$

Amount of pearlite:

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

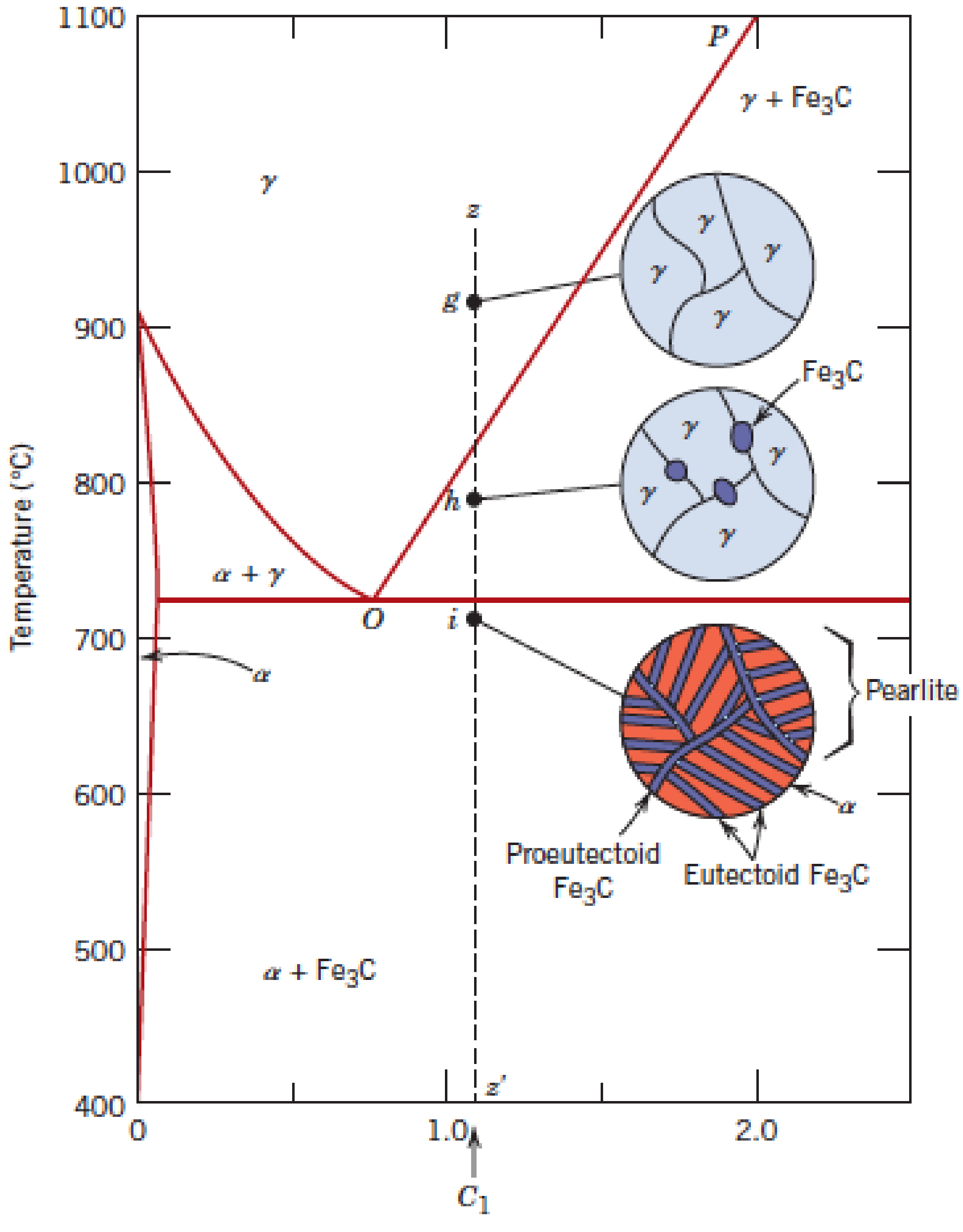
Amount of total ferrite:

$$f_\alpha = \frac{6.70 - C_0^{'}}{6.70 - 0.022}$$

Amount of total cementite:

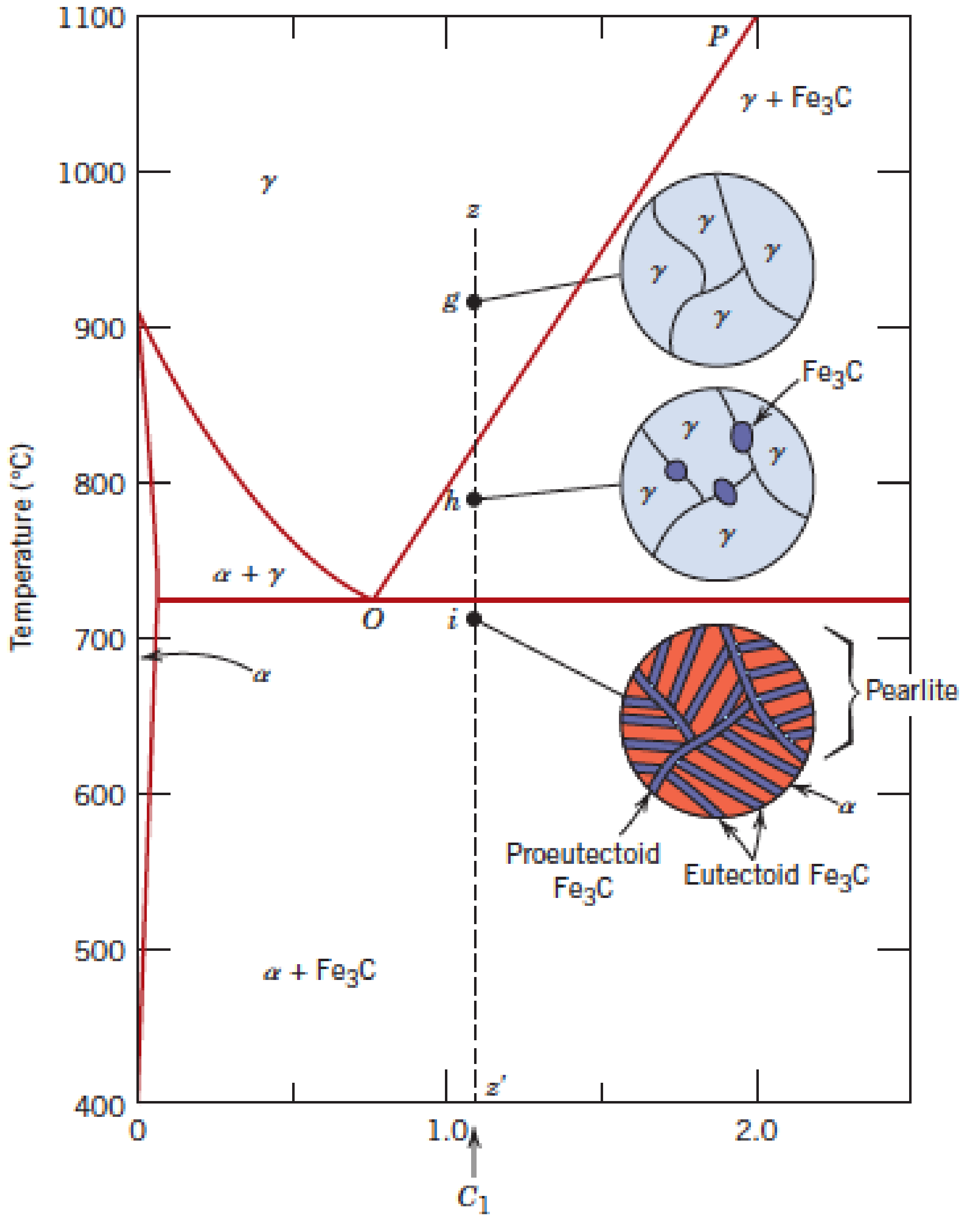
$$f_c = \frac{T}{6.70 - 0.022}$$

Hypereutectoid composition



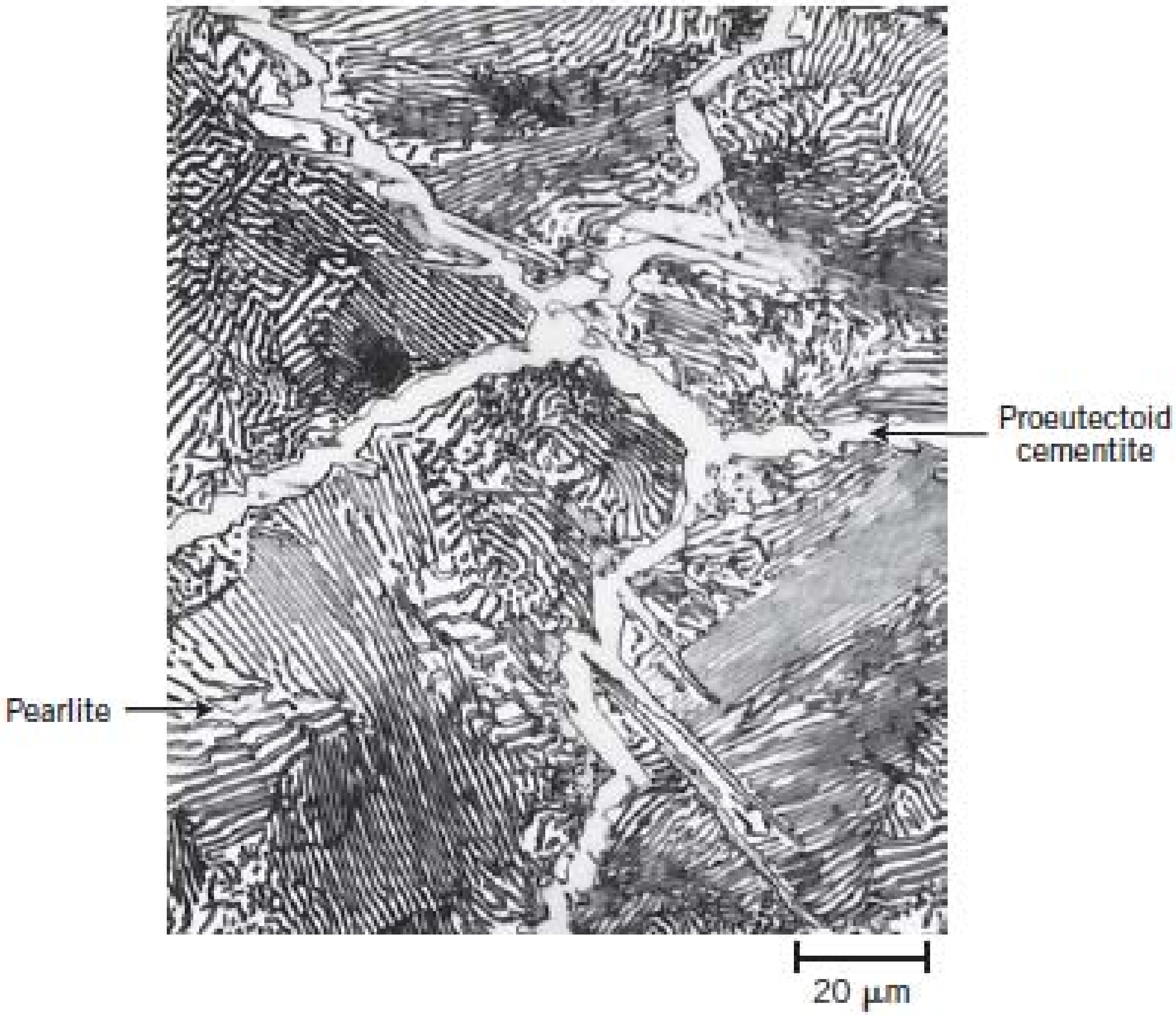
- The hypereutectoid region corresponds to the right of the eutectoid composition, more than 0.76 wt.% C.
- The discussion of microstructure evolution is essentially the same as for proeutectoid composition

Hypereutectoid composition



- However, in hypoeutectoid steels the phase formed prior eutectoid temperature is proeutectoid ferrite
- In case of hypereutectoid steels the corresponding phase is proeutectoid cementite

Hypereutectoid steel microstructure

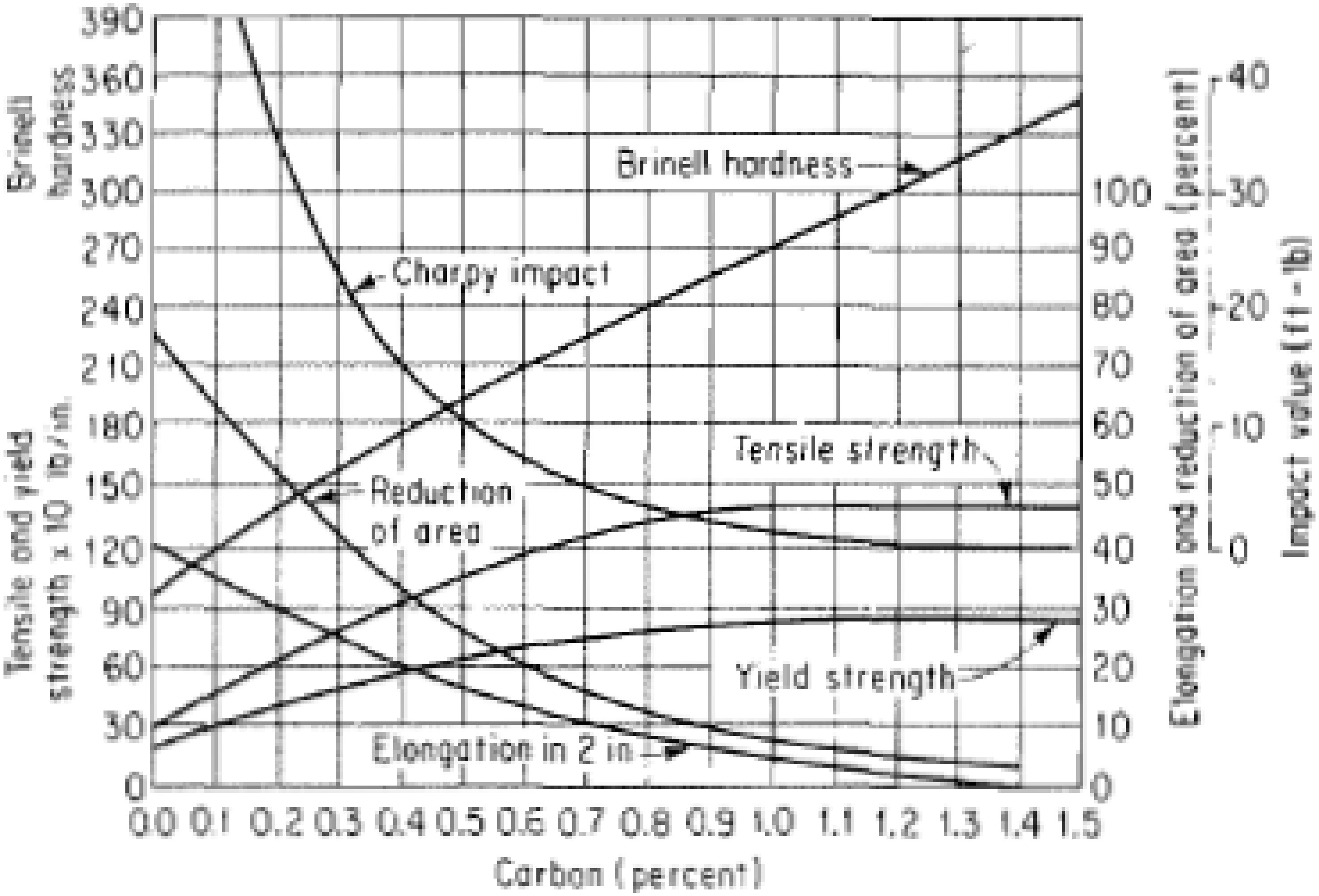


Lecture 2

Effect of C-content on steel properties

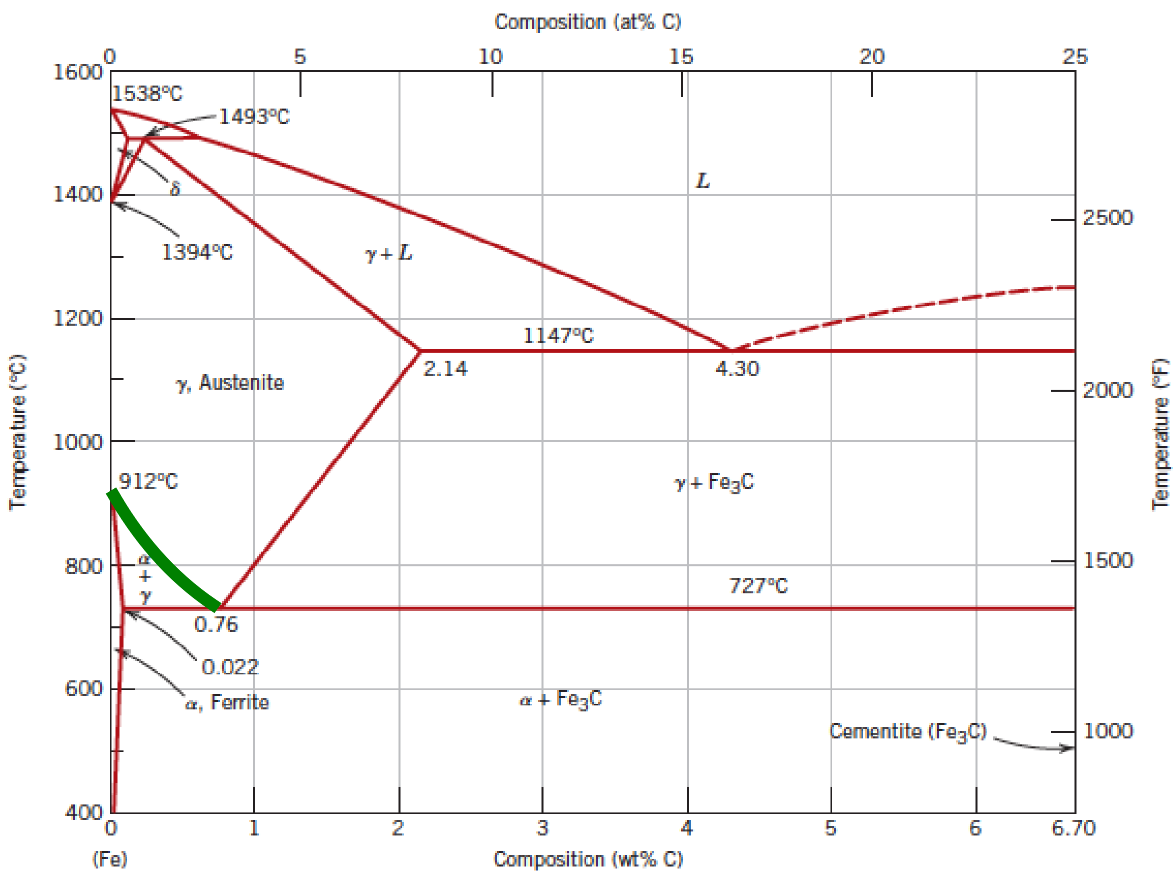
- Mechanical properties of steel depend upon the amounts of ferrite and cementite and their distribution
- Ferrite is soft with low tensile strength
- Cementite is very hard with low tensile strength ➔ brittle
- Pearlite, a mixture of these two phases, has a much higher tensile strength
- In hypoeutectoid steels, with ↑ C-content, tensile strength ↑, Brinell hardness ↑, ductility ↓ and Charpy impact energy ↓
- For hypereutectoid steels, with ↑ C-content, tensile strength may ↓ but hardness continuously ↑ (due to the very hard continuous cementite network).

Effect of C-content on steel properties



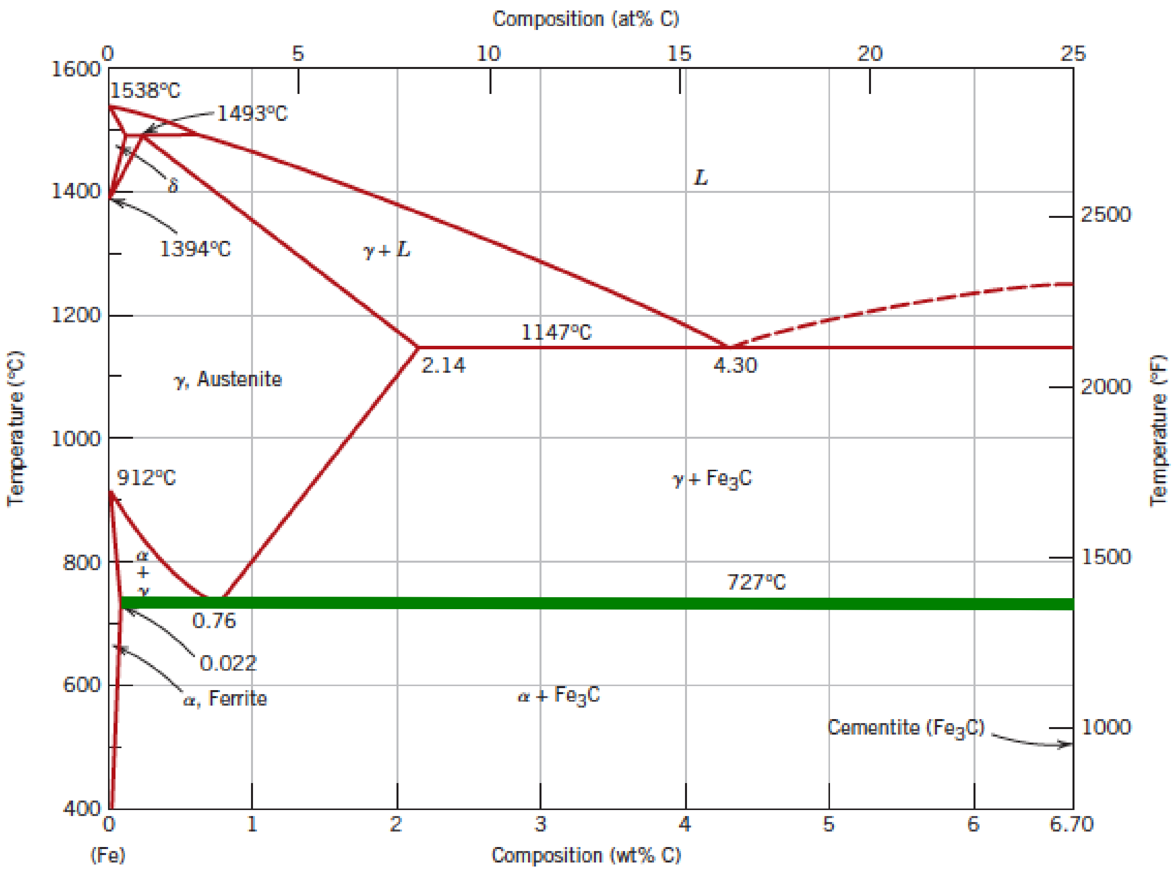
Critical temperature lines

Upper critical temperature (A_{C3}): It is the temperature, below which ferrite starts forming from austenite in hypoeutectoid alloys.



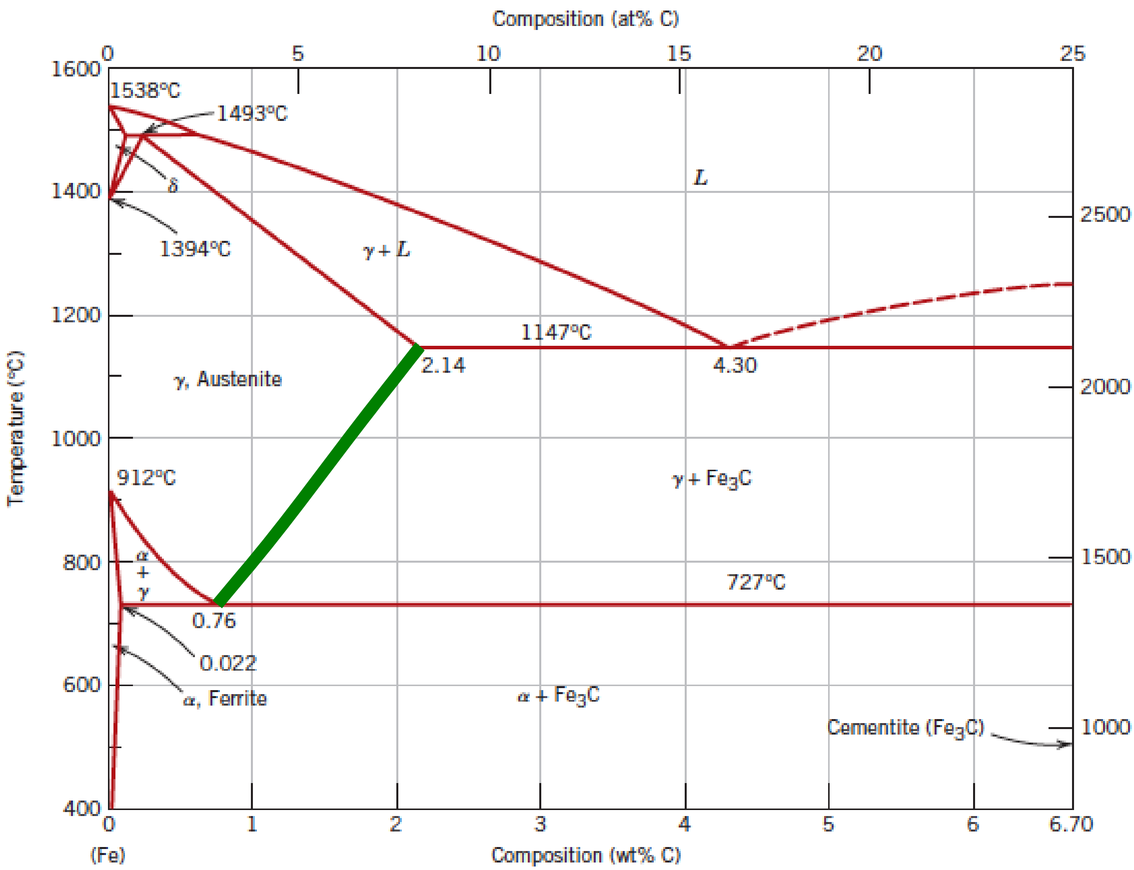
Critical temperature lines

Lower critical temperature (A_{C1}): It is the temperature of the austenite to pearlite eutectoid transformation. Austenite does not exist below this temperature.



Critical temperature lines

Upper critical temperature (A_{Cm}): It is the temperature, below which cementite starts forming from austenite in hypereutectoid alloys.



Summary: equilibrium microstructures