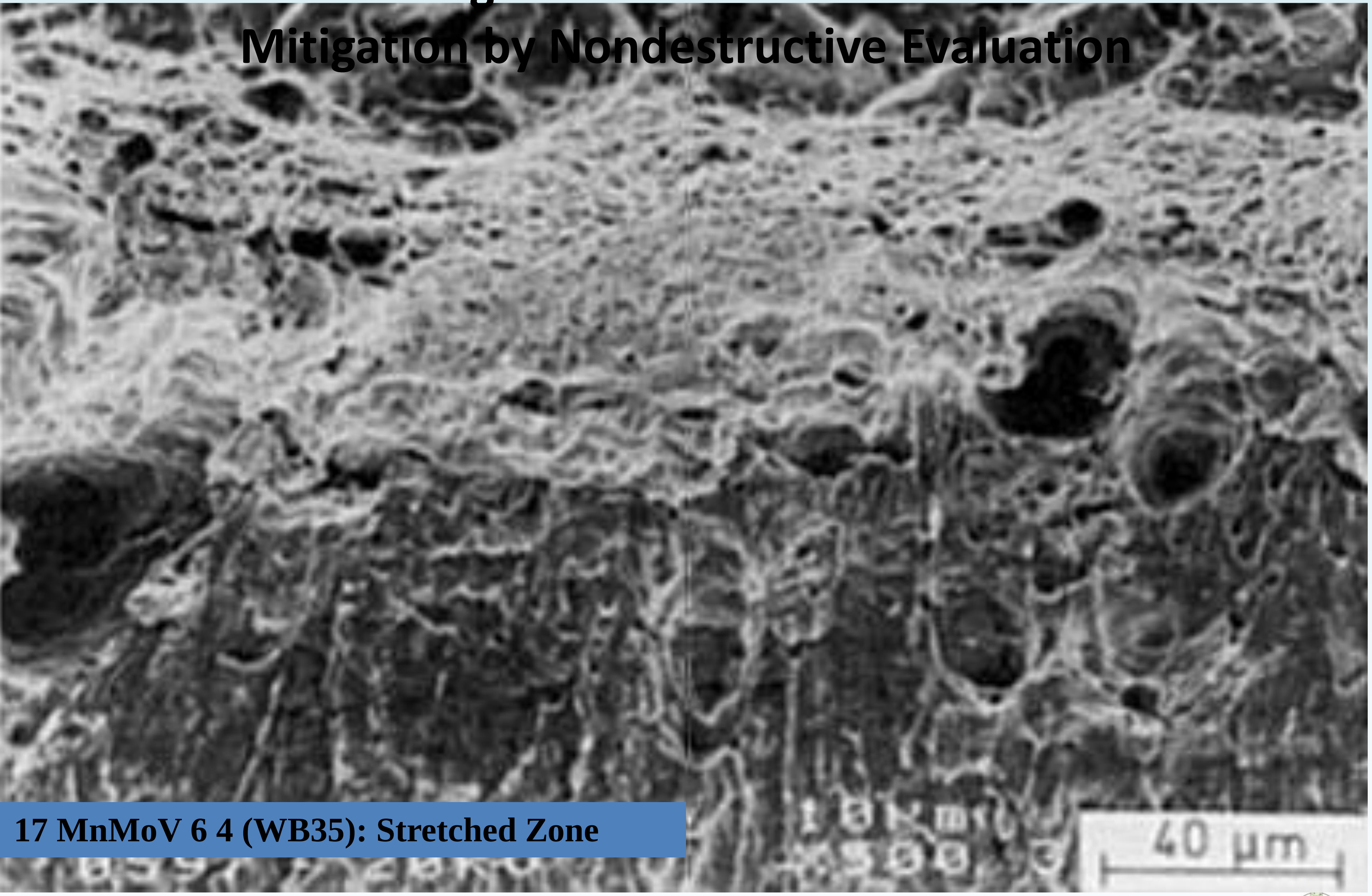
Material Degradation of Nuclear Structures
Mitigation by Nondestructive Evaluation



17 MnMoV 6 4 (WB35): Stretched Zone

Material Degradation of Nuclear Structures Mitigation by Nondestructive Evaluation

Material Degradation of Nuclear Structures Mitigation by Nondestructive Evaluation

STEEL

GENERAL DEFINITION

Oxford dictionary:

A hard, strong grey or bluish-grey alloy of iron with carbon and usually other elements, used as a structural and fabricating material

MacMillan Dictionary:

A strong metal made from a mixture of iron and carbon

STEEL

The Free Dictionary:

A generally hard, strong, durable, malleable alloy of iron and carbon, usually containing between 0.2 and 1.5 percent carbon, often with other constituents such as manganese, chromium, nickel, molybdenum, copper, tungsten, cobalt, or silicon, depending on the desired alloy properties, and widely used as a structural material.

Focus on Steel

STEEL

Iron alloy containing carbon
from as low as 0.03 % (as in ingot steel)
to 2.5 % by weight (as in cast iron),
and varying amounts of other elements
(mainly chromium, manganese, molybdenum, nickel, and silicon)
depending on its end use.

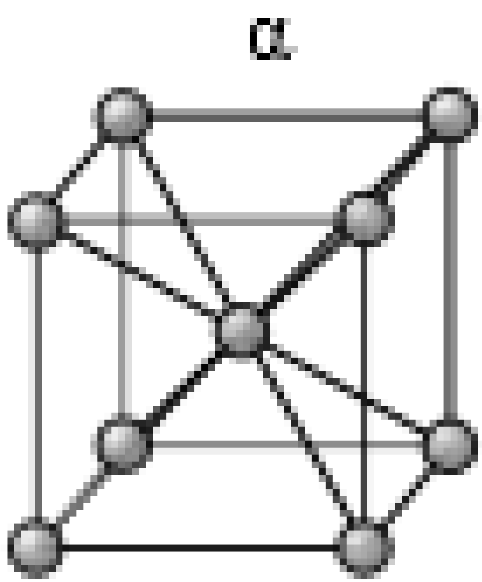
STEEL

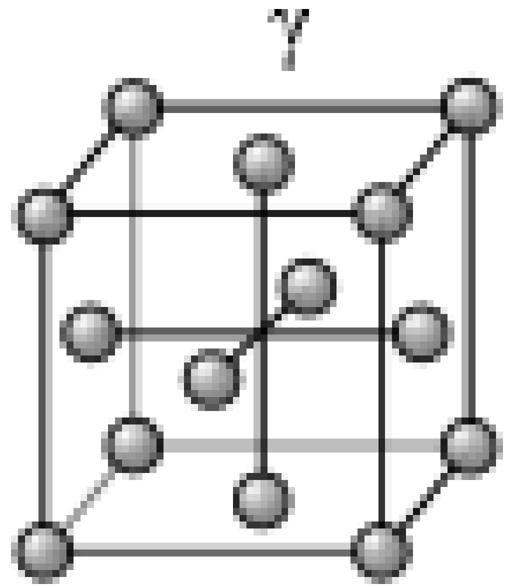
Higher amounts of carbon make the steel more fluid and castable, and lower amounts make it purer for specialized purposes such as electrical steel and stainless steel.

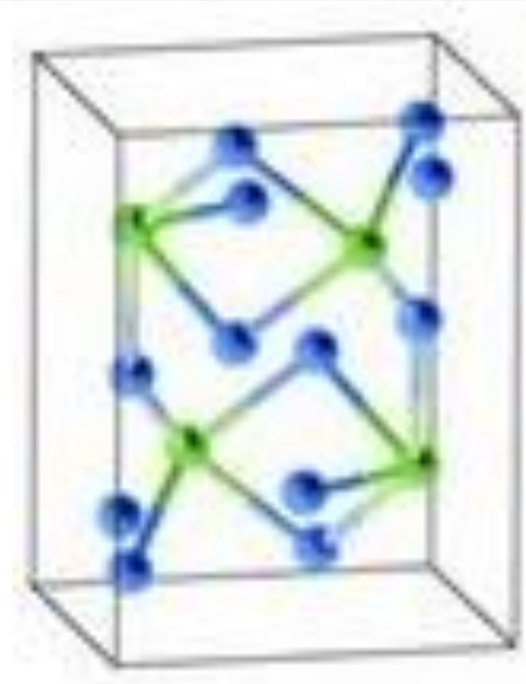
Carbon steel exists in three main stable crystalline forms:

Ferrite (body centered cubic crystal),
Austenite (face centered cubic crystal)
Cementite (orthorhombic crystal).

Focus on Steel







alpha iron (ferrite) **gamma iron (austenite)** **cementite Fe_3C**

Allotropes of iron

Focus on Steel

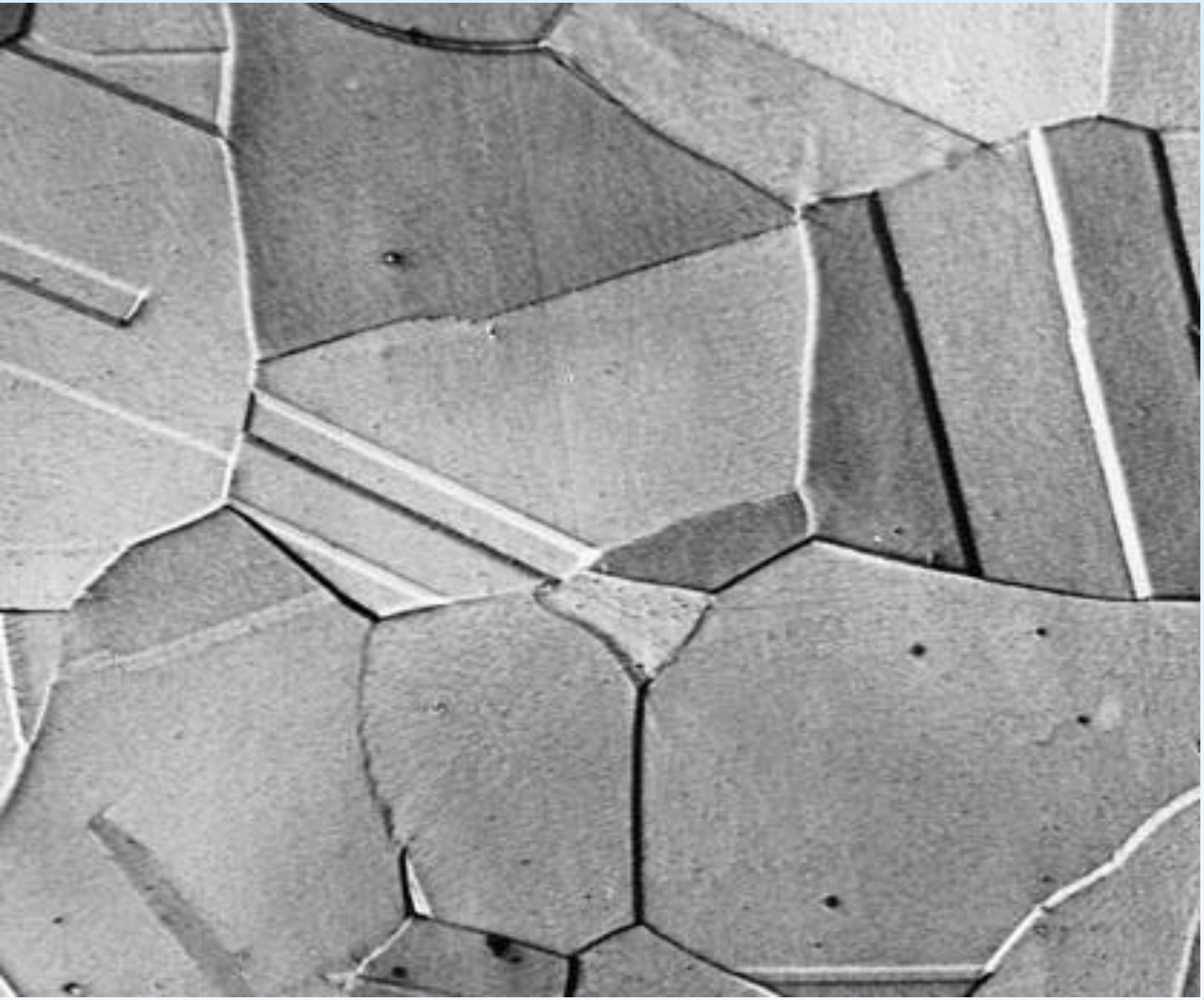
Ferrite (alpha iron) crystal structure

Ferrite, also known as α-*ferrite* (α-Fe), constitutes of pure iron with a bcc structure (body-centered cubic).

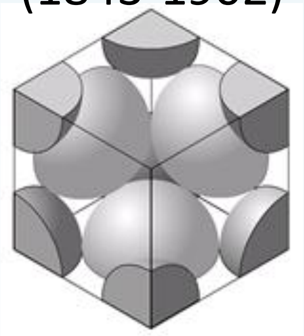
The crystalline structure gives steel (& cast iron) ferromagnetic properties.

Carbon steels with up to 0.2 wt% C (mild steels) consist mostly of ferrite

Focus on Steel



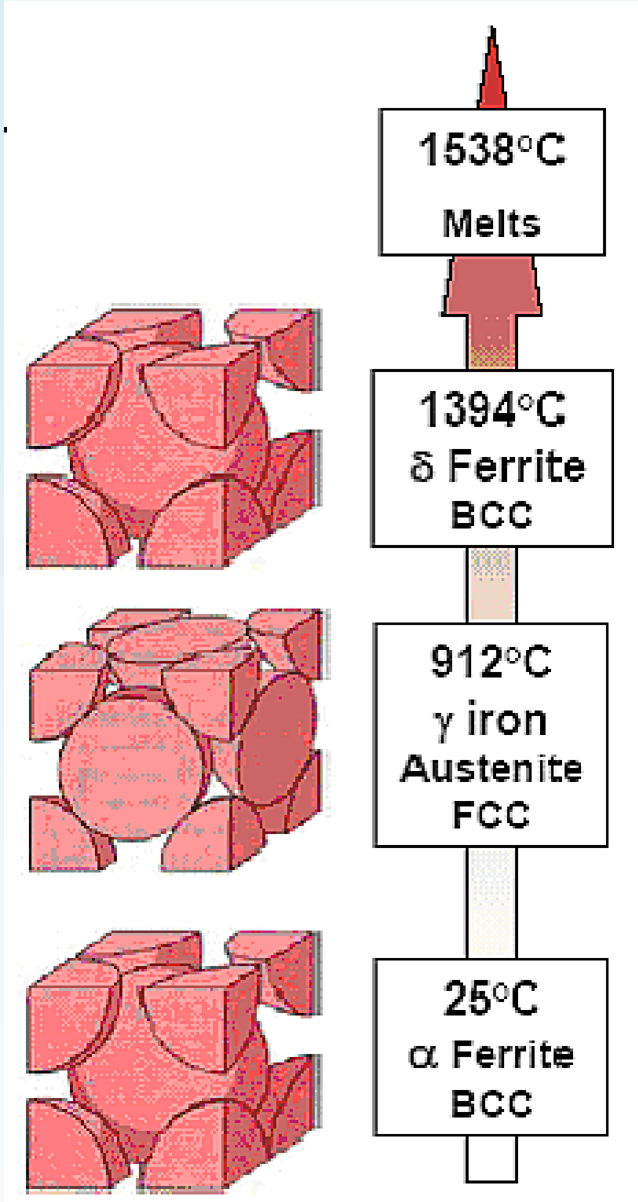
Austenite, also known as γ-*ferrite* (γ-Fe), constitutes of pure iron with a fcc structure (face-centered cubic).
It is only possible in carbon steel at high temperature or as a solid solution of iron with an alloying element.
It is a paramagnetic allotrope of iron.
William Chandler Austen (1843-1902)



Austenite (gamma iron) crystal structure

Focus on Steel

PURE FERRITE



Ferrite above the critical temperature A_2 (Curie temperature) of 771 °C, is beta ferrite or beta iron (β-Fe). It is paramagnetic rather than ferromagnetic

771°C – 912°C: paramagnetic beta ferrite (β-Fe).

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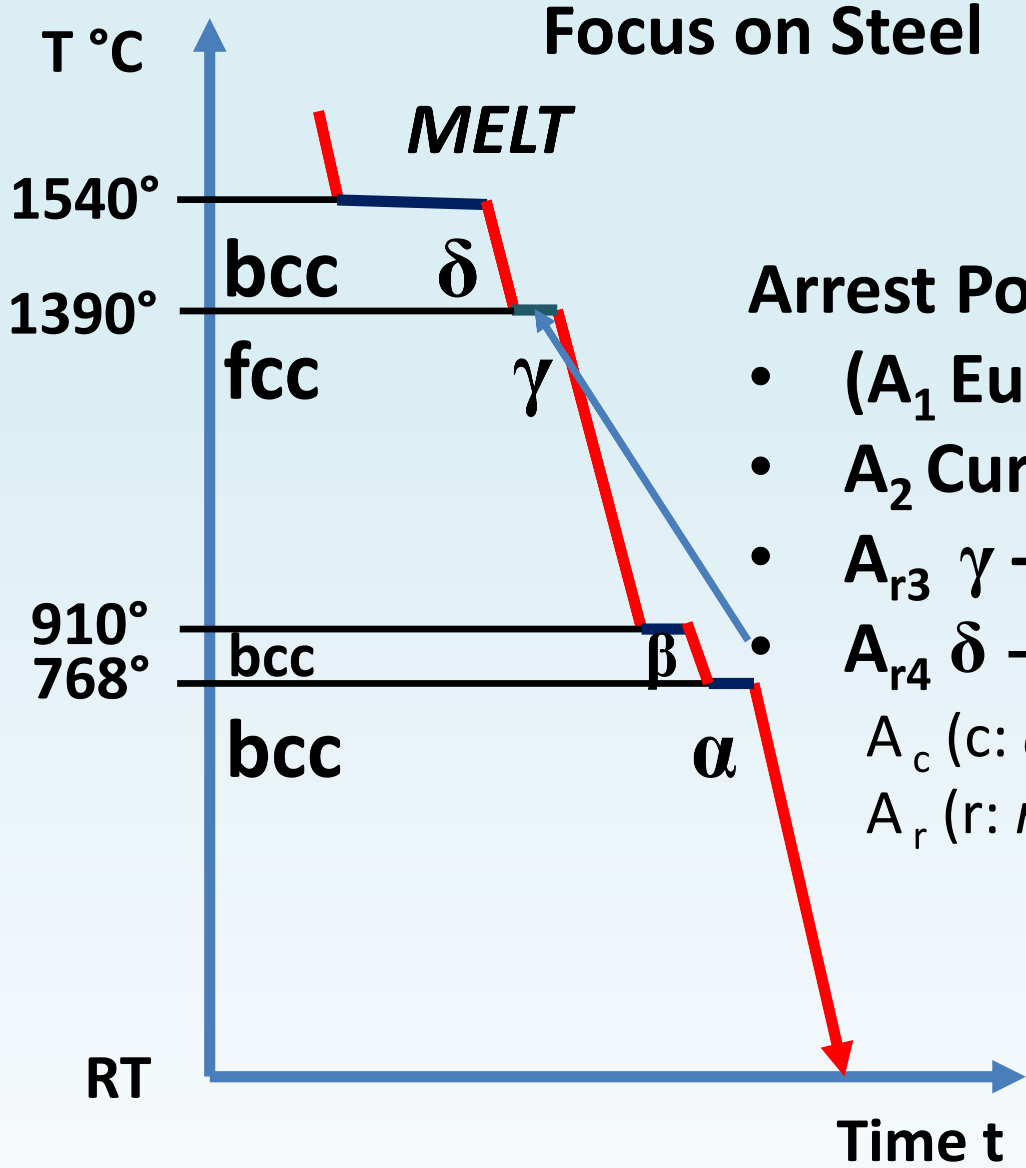

Arrest Points A:

- **(A_1 Eutectoid temperature)**
- **A_2 Curie Temperature** 771°C
- **A_{r3} $\gamma - \beta$ transformation**
- **A_{r4} δ - γ transformation**

A_c (c: *chauffage* = heating)

A_r (r: *refroidissement* = cooling)

Scheme of Thermal Arrest (pure iron)

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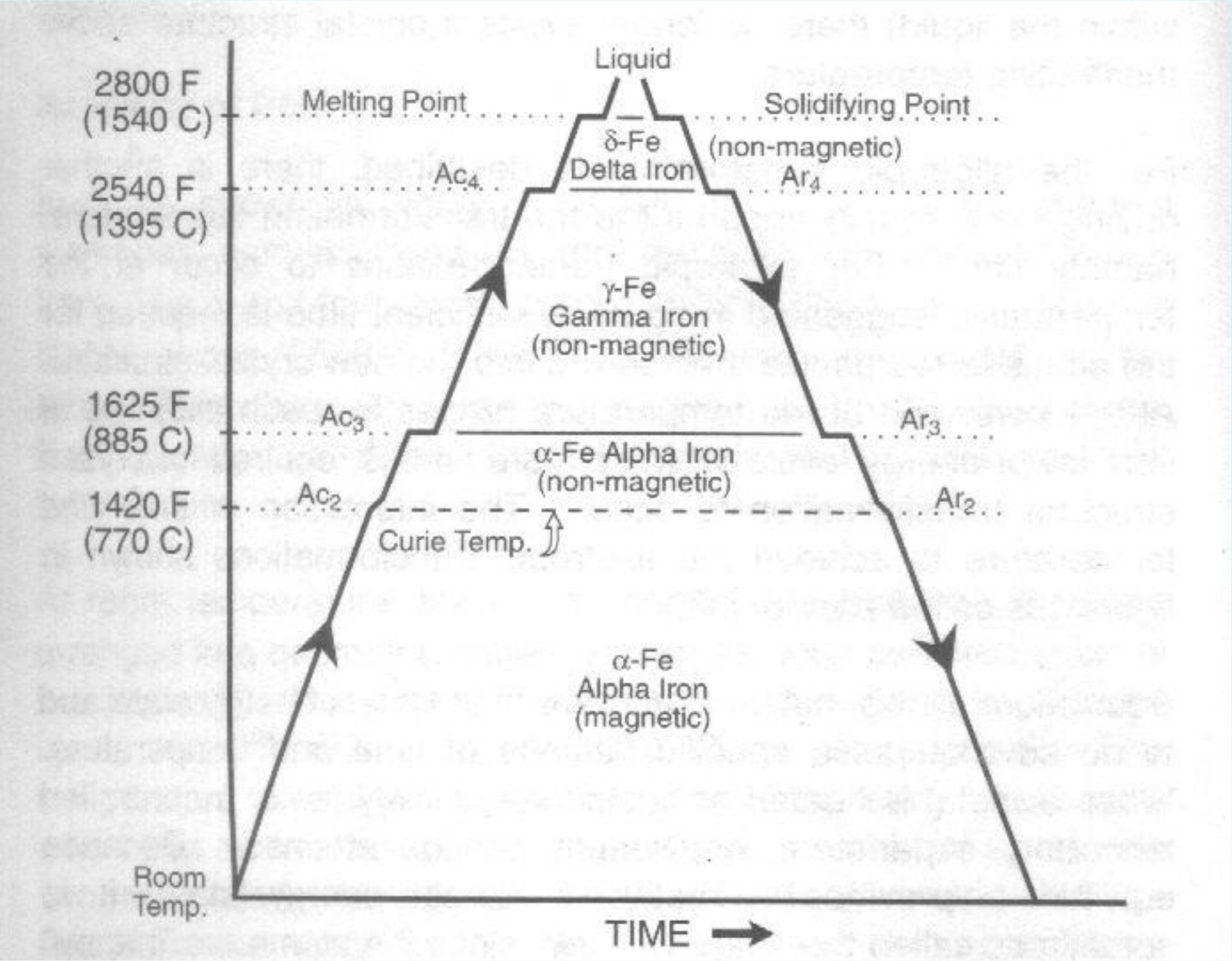


Allotropy of pure iron upon heating and cooling

A_2 – a critical temperature for induction heating

Beta ferrite and the A_2 critical temperature are very important in induction heating of steel, such as for surface-hardening heat treatments.

Steel is typically austenitized at 900–1000 °C before it is quenched and tempered.

The high-frequency alternating magnetic field of induction heating heats the steel by two mechanisms below the Curie temperature:

- resistance or Joule (I^2R) heating
- ferro-magnetic hysteresis losses.

Above the A_2, the hysteresis mechanism disappears and the required amount of energy per degree of temperature increase is substantially larger than below A_2

Load-matching circuits may be needed to vary the impedance in the induction power source to compensate for the change.

Focus on Steel

STEEL: An Alloy of Iron and Carbon

We may understand the Diversity of Alloys of different Properties and Applications beginning with the IRON – CARBON Phase Diagram

***There is a third (meta)stable phase:
CEMENTITE, that by time transforms into GRAPHITE:
It is an inter-metallic compound with 6.67% C.
Cementite is very hard and brittle***

Focus on Steel

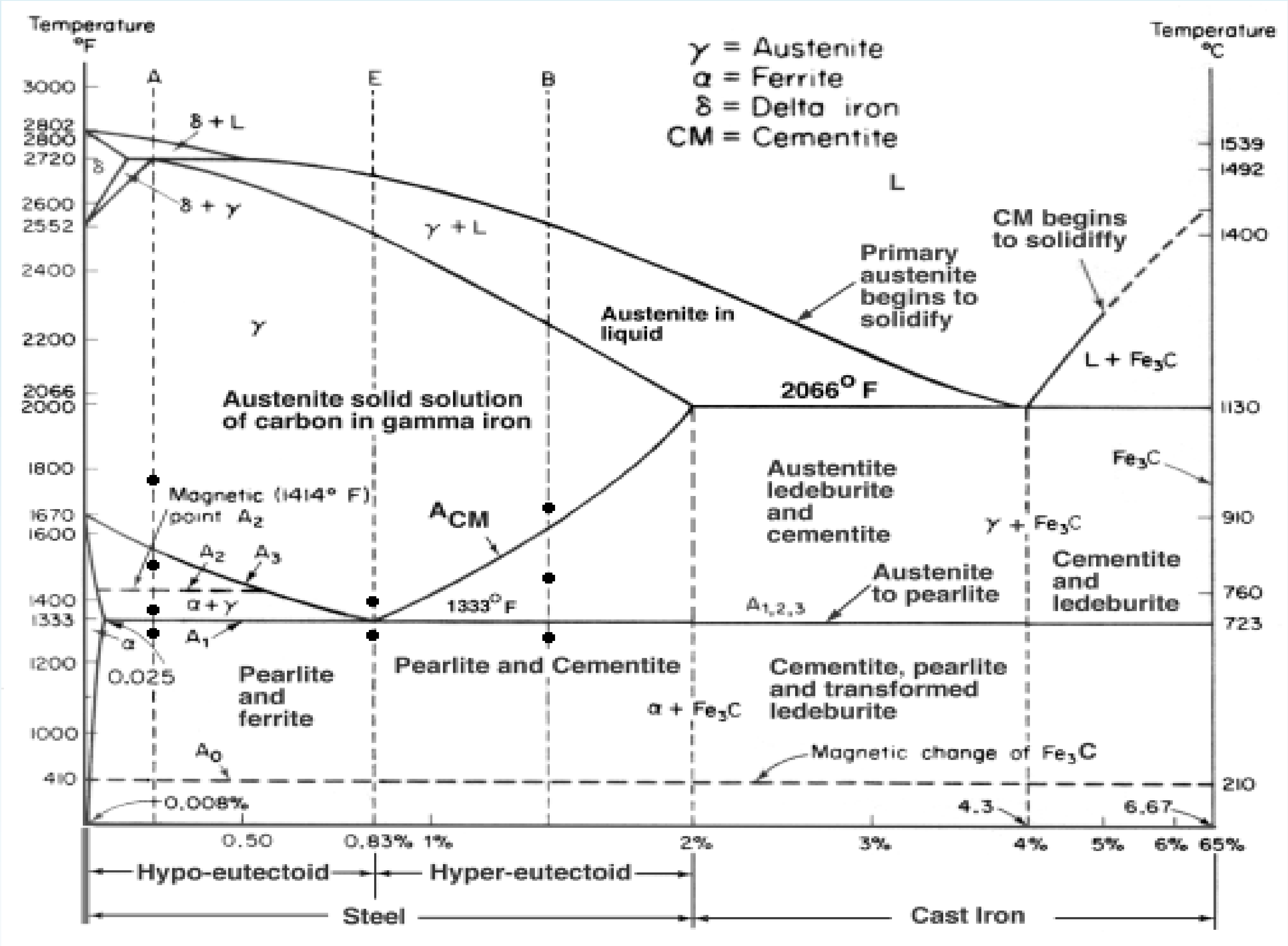
Cementite Fe_3C
is iron carbide with an orthorhombic crystal structure.

It is hard & brittle, essentially a ceramic in its pure form.

In carbon steel, it either forms from austenite during cooling or from martensite during tempering.

Microstructure of cementite

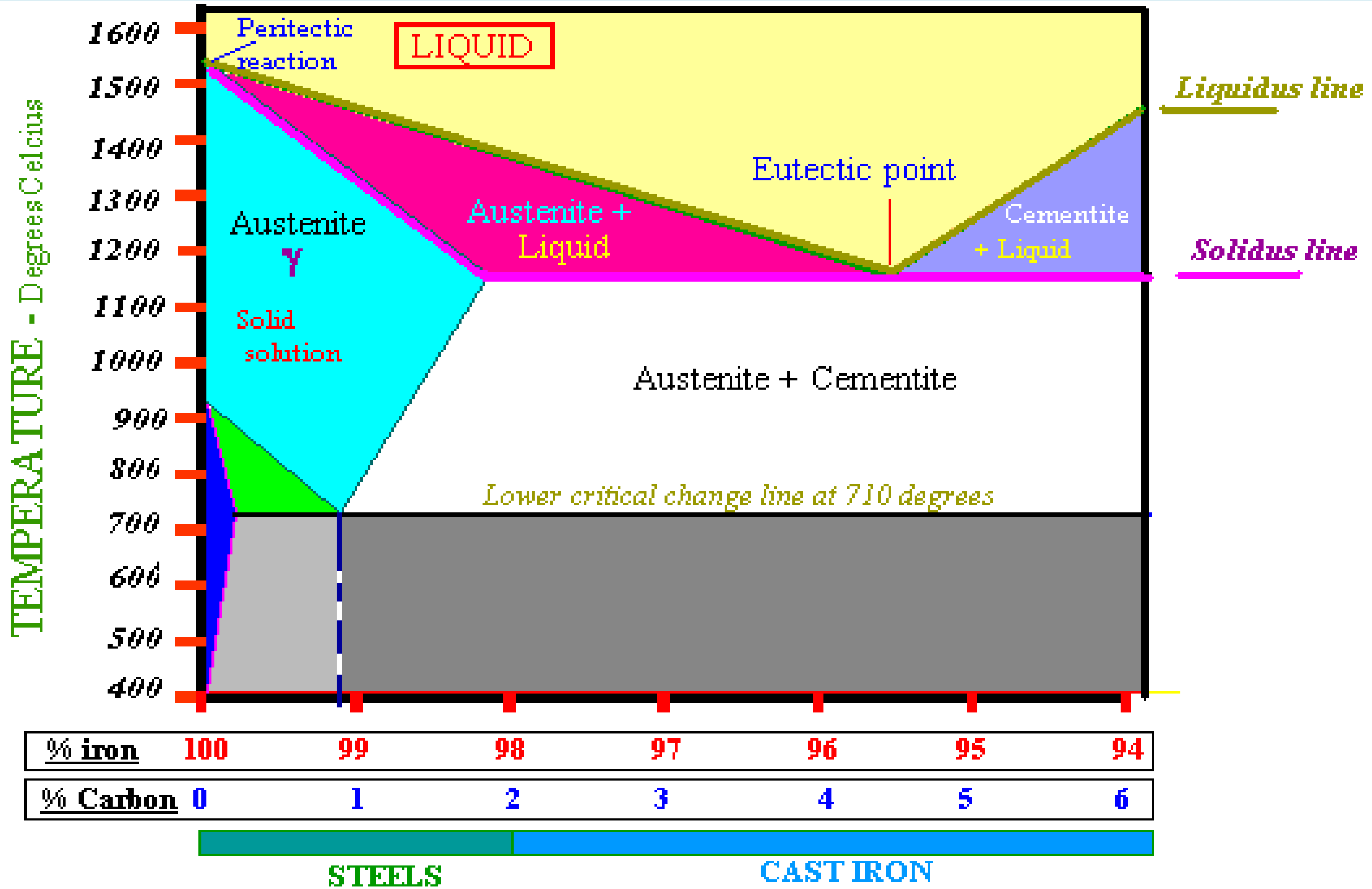
Focus on Steel



Fe-Fe_3C Phase Diagram

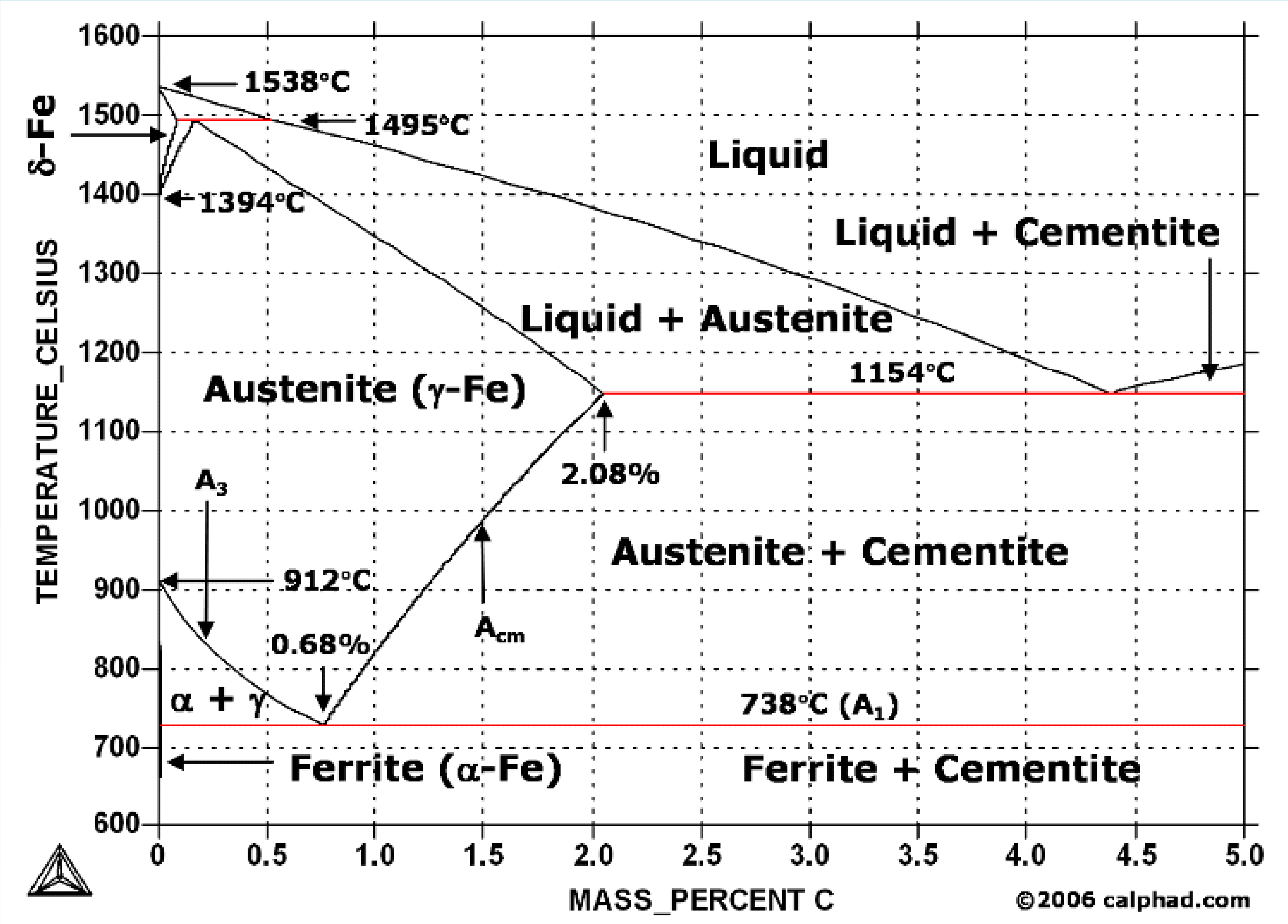
(*Materials Science and Metallurgy*, 4th ed., Pollack, Prentice-Hall, 1988)

Focus on Steel



The Iron Carbon Equilibrium Diagram

Focus on Steel



Computed Fe-C phase diagram

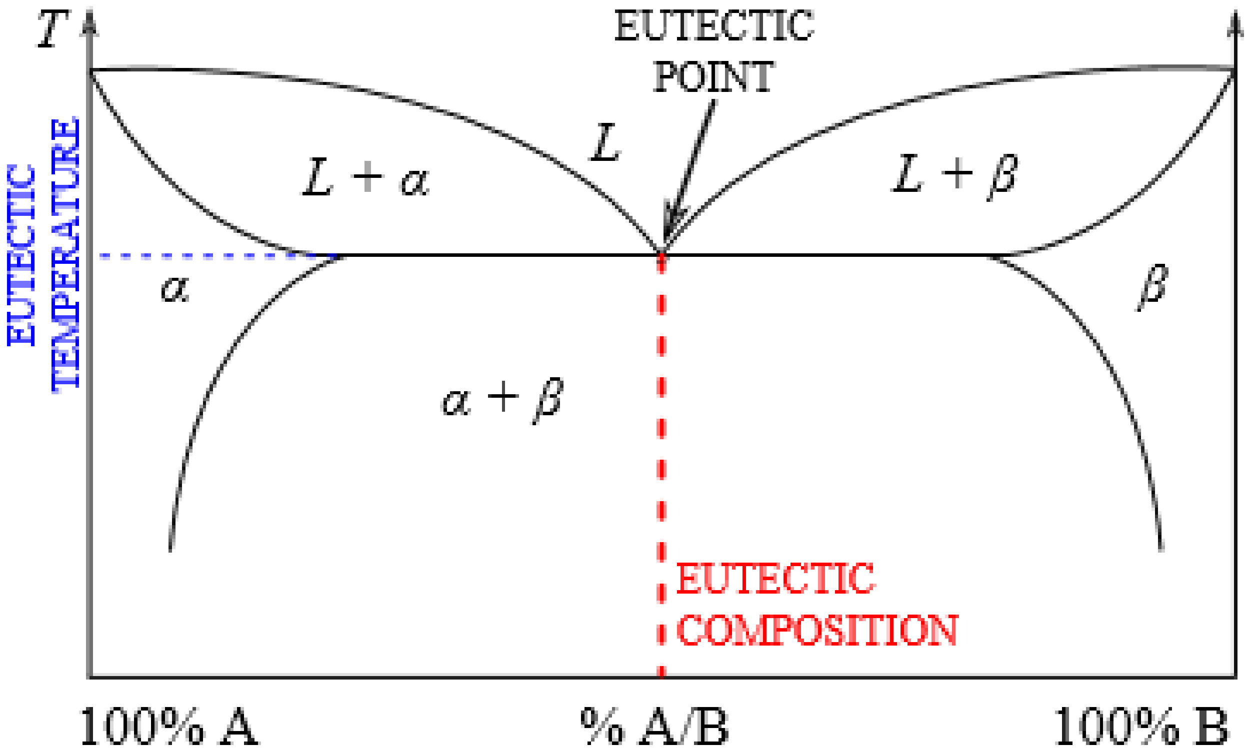
Thermo-Calc, coupled with PBIN thermodynamic database

Focus on Steel – Phase Transformations

Eutectic System – a mixture of

chemical compounds or elements that have a single chemical composition that solidifies at a lower temperature than any other composition made up of the same ingredients.

This composition is known as the eutectic composition, the temperature at which it solidifies as the eutectic temperature



The eutectic reaction is defined as follows:

$$\text{Liquid} \xrightarrow[\text{cooling}]{\text{eutectic temperature}} \alpha \text{ solid solution} + \beta \text{ solid solution}$$

As an **invariant reaction**,
it is in thermal equilibrium;
The liquid and two solid solutions
all coexist at the same time
and are in chemical equilibrium.

There is a thermal arrest
for the duration of
the change of phase
during which the temperature
of the system does not change.

On a phase diagram the intersection of the eutectic temperature and the eutectic composition gives the *eutectic point*.

Focus on Steel

The eutectoid reaction

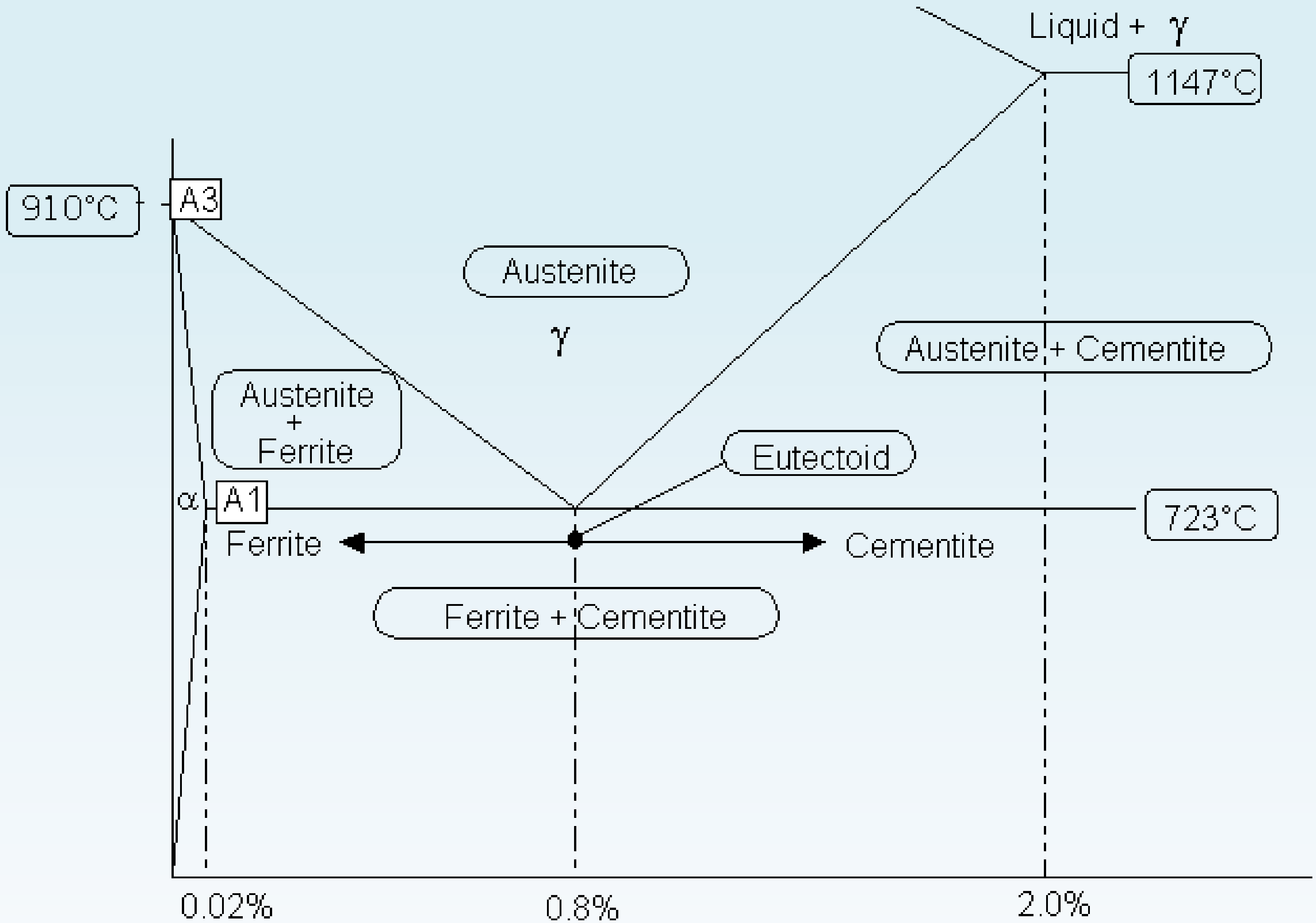
A *eutectoid reaction* is a three-phase reaction by which, on cooling, a solid transforms into two other solid phases at the same time.

The Pearlite Reaction:

$$\gamma\ (\mathrm{Fe}) \xrightarrow[0.76\%\ \mathrm{C}]{727\ ^{\circ}\mathrm{C}} \alpha\ (\mathrm{Fe}) + \mathrm{Fe_3C}$$

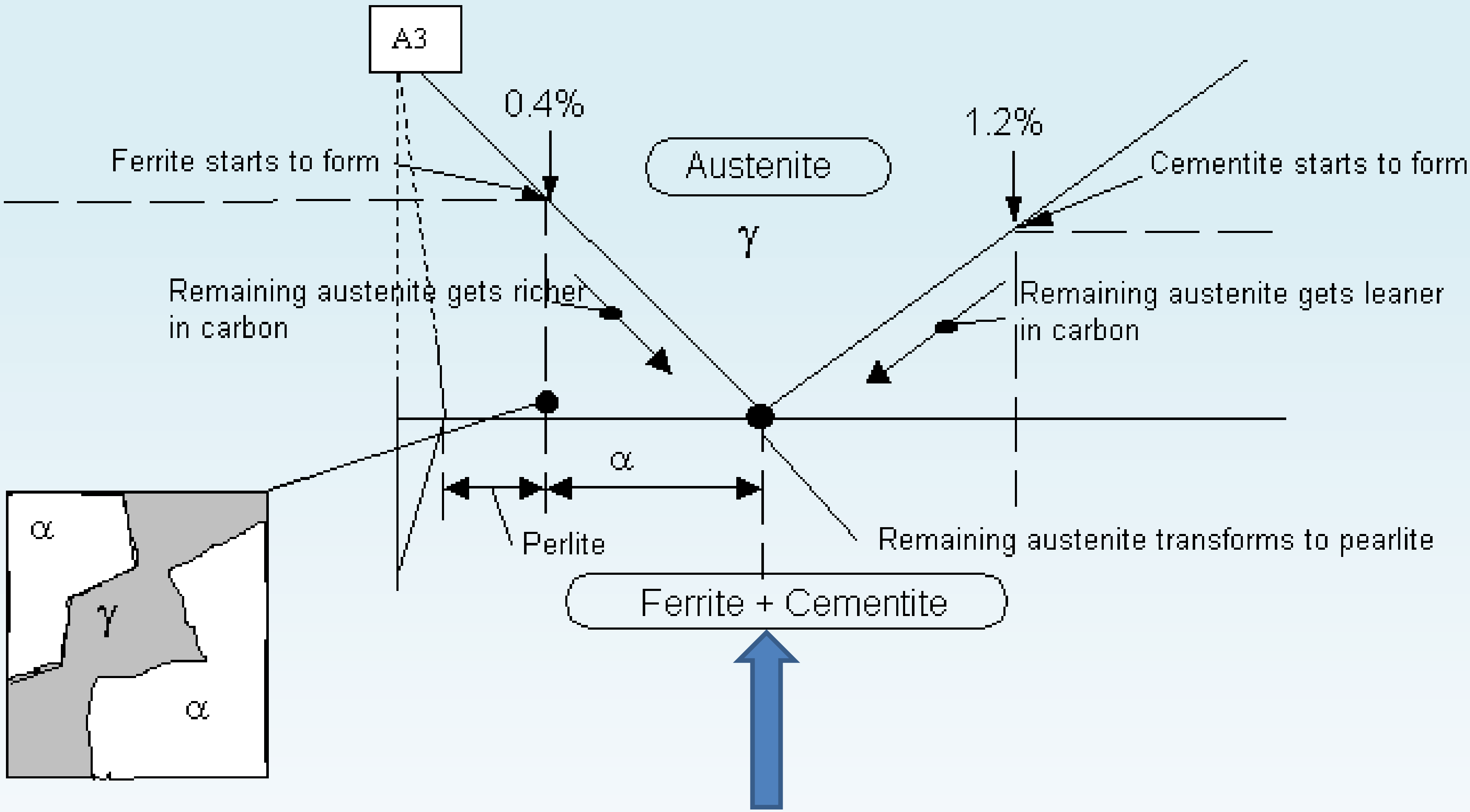
On a phase diagram the intersection of the eutectoid temperature and the eutectoid composition gives the *eutectoid point*.

Focus on Steel



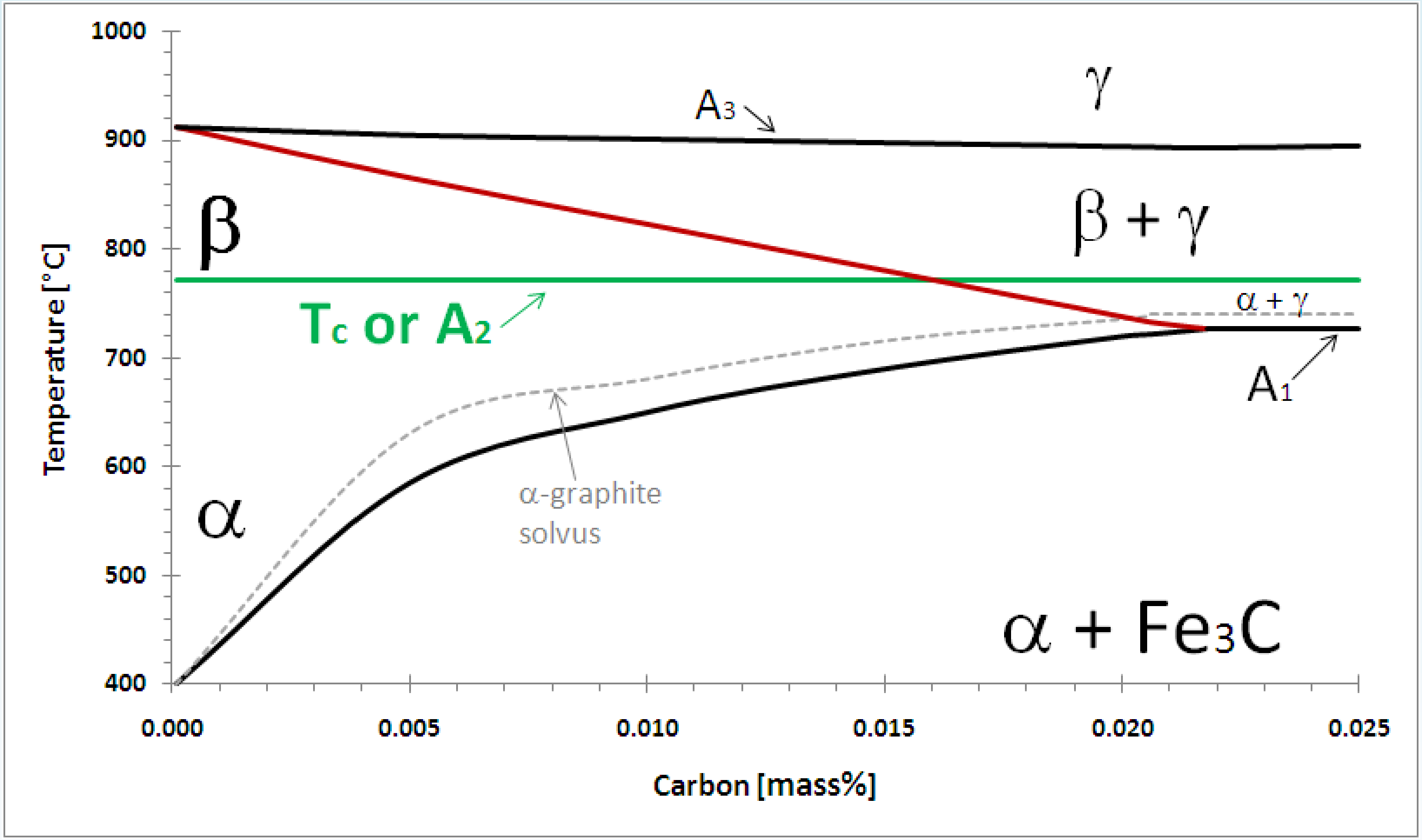
The steel part of the iron - carbon diagram

Focus on Steel



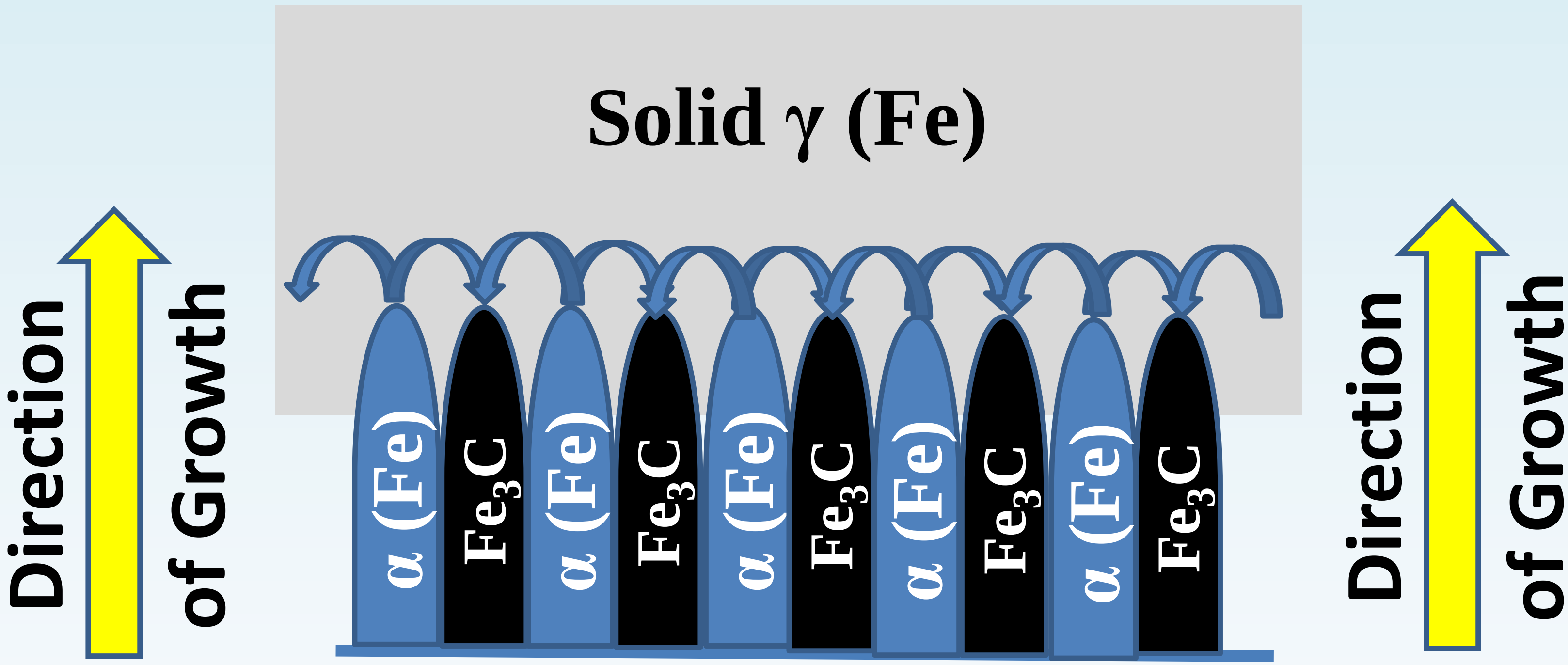
Cooling Transformation – the Eutectoid Reaction

Focus on Steel – Steel Qualities



The Pearlite Reaction:

$$\gamma\ (Fe) \longrightarrow \alpha\ (Fe) + Fe_3C$$



Eutectoid

Pearlite is not a phase, but a mixture of two phases: ferrite and cementite

Focus on Steel – Steel Qualities

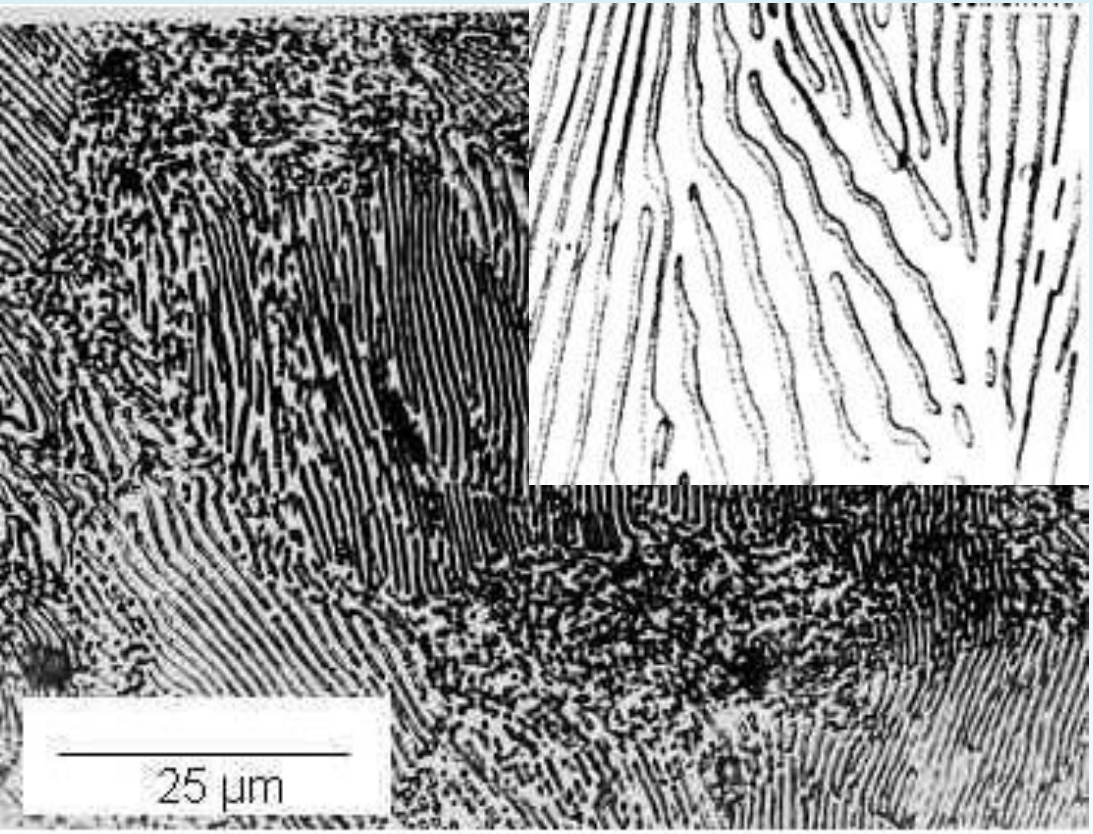
www-g.eng.cam.ac.uk/mmg/teaching/typd/addenda/definition.html

because it has a pearly look).

Teach Yourself Phase Diagrams (Google)

Pearlite

A mixture of ferrite and cementite.



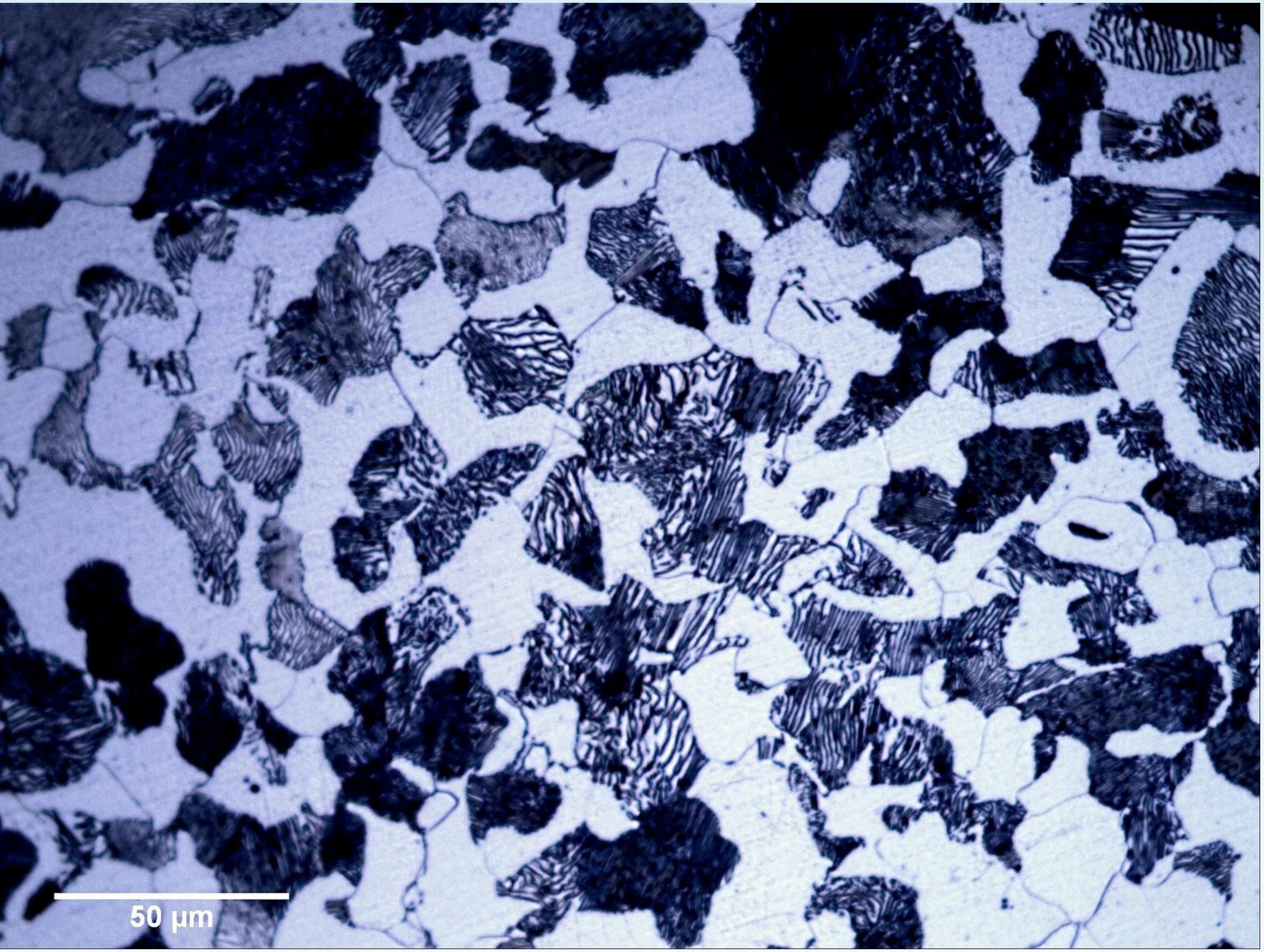
Photomicrograph of Pearlite Structure
(Dark bands are cementite)

PEARLITE (a + Fe_3C)
It is the eutectoid mixture containing 0.77 % Carbon.
It is formed at 1333^{o}F on very slow cooling.

Pearlite grain structures resemble human fingerprints. Steel with 0.77 percent carbon consists of uniform pearlite at room temperature.

Light background is the ferrite matrix, dark lines are the cementite network

Focus on Steel

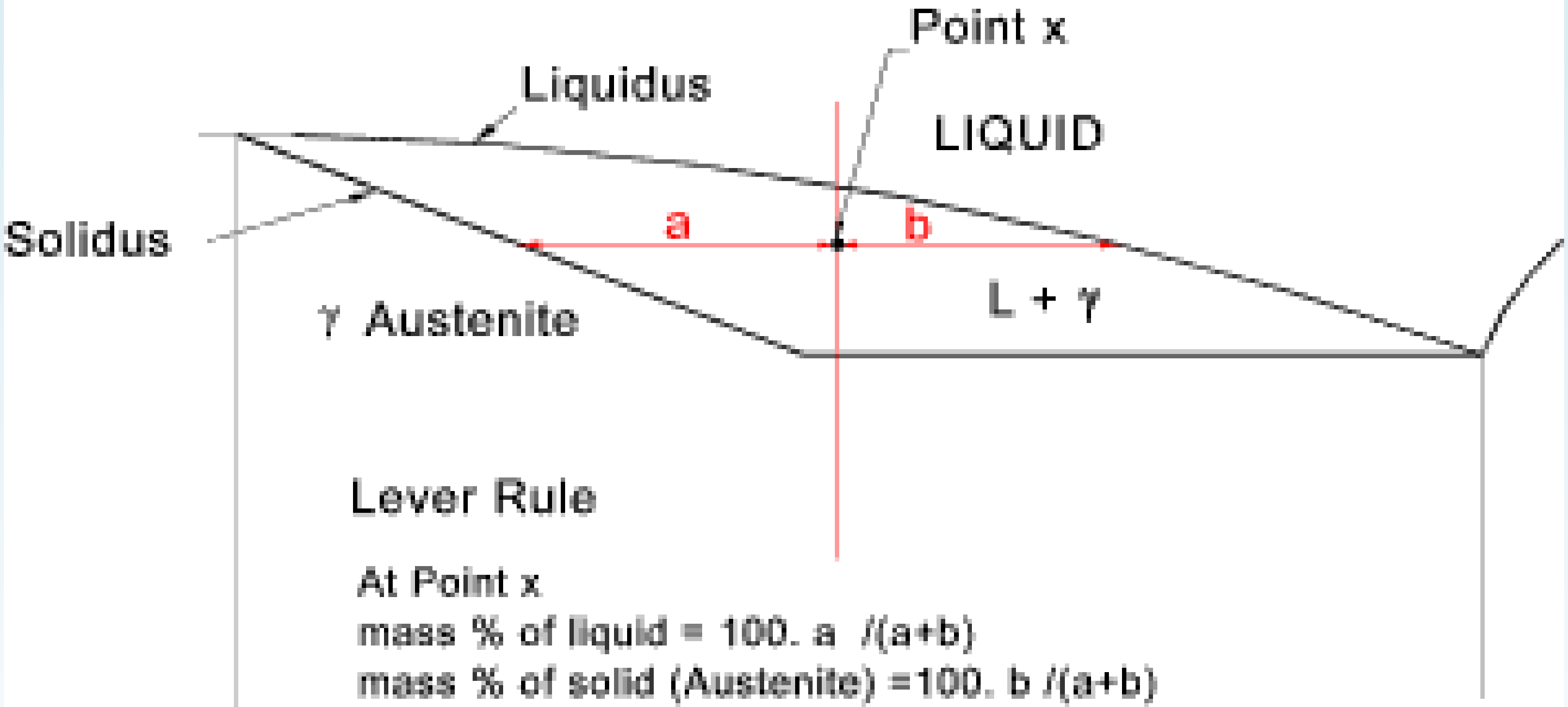


Nonalloyed Steel
0,45% C (C45)

Crystal Mixture formed by ferrite grains (white) and pearlite grains (dark) with typical lamellar structure composed of alternating layers: alpha-ferrite (88 wt%) and cementite (12 wt%)

Lever Rule

The lever rule can be applied to any phase region.
It provides an indication of the proportions of the constituent parts at any point on the phase diagram.

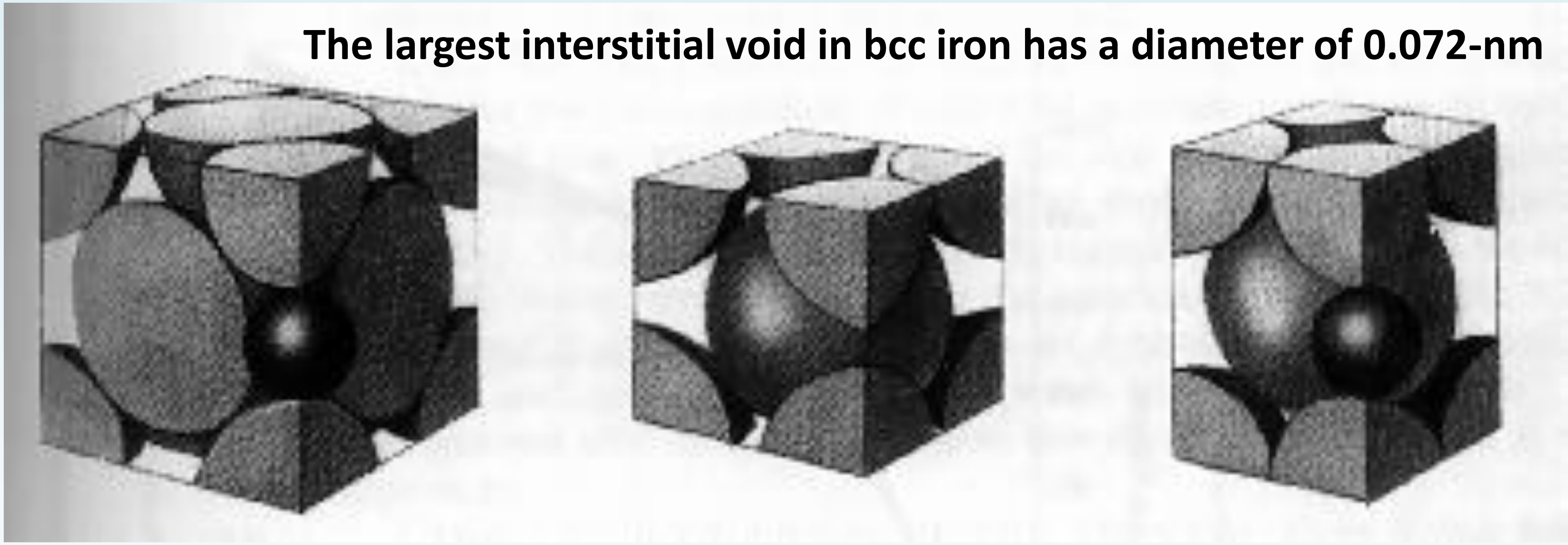


Applied to the eutectoid point (0,80% C at 723°C):
Wt% Ferrite = 100 (6,67 -0,8)/ 6,67- 0,02) = 88%
Wt% Cementite = 100 (0,8- 0,02) /6,67- 0,02) = 12%

Focus on Steel

Only a small amount of carbon can be dissolved in ferrite;
the maximum solubility is about 0.02 wt% at 723 °C and 0.005% carbon at 0 °C.

Carbon dissolves in iron interstitially,
with the carbon atoms being about twice the diameter of the interstitial "holes",
so that each carbon atom is surrounded by a strong local strain field.



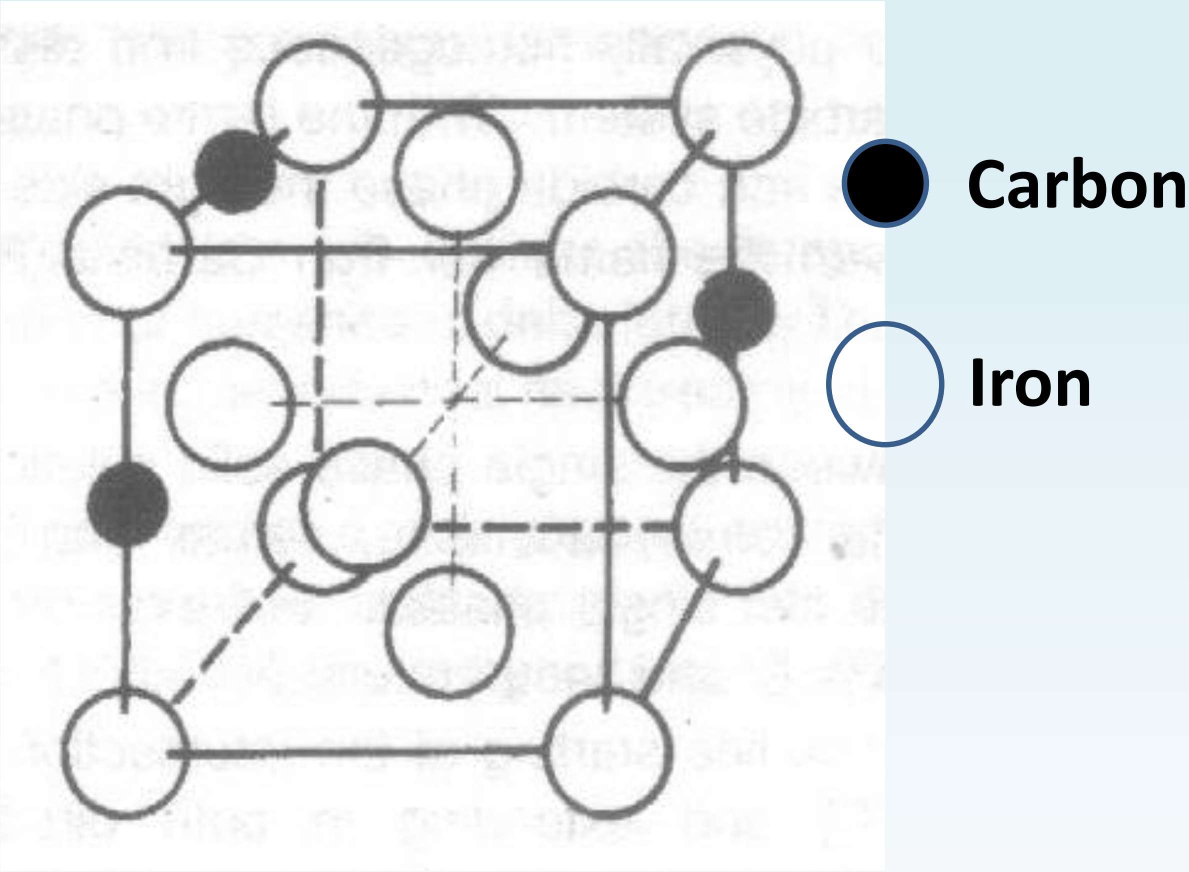
Carbon dissolved interstitially in bcc ferrite

Focus on Steel

The austenite has more space between the iron atoms dissolving more carbon atoms, a little less than 0.8% at the eutectoid point .

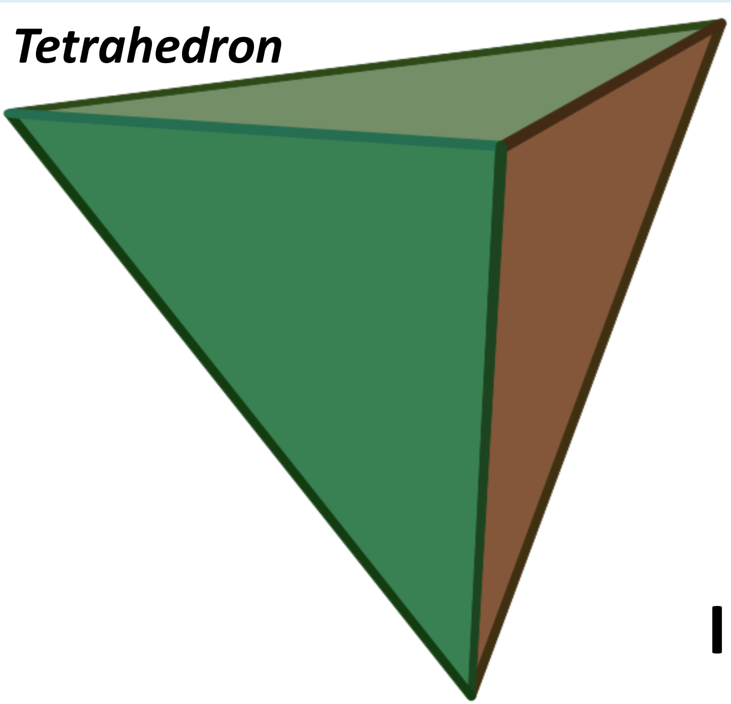
The much larger phase field of austenite indicates clearly the considerably grater solubility of carbon in gamma-iron, the maximum value being 2.08 wt.% at 1154 °C.

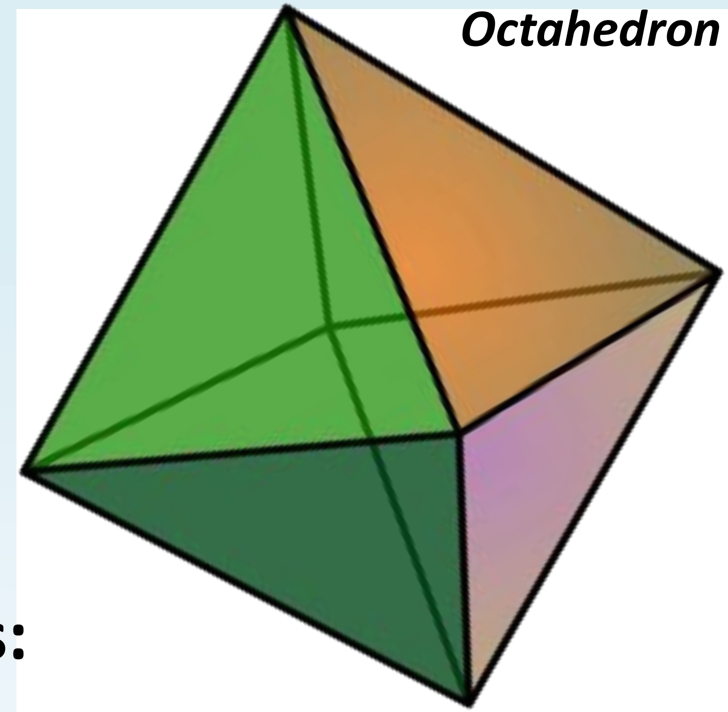
The hardening of carbon steels is based on this difference in the solubility of carbon in alpha-iron and gamma-iron



Carbon dissolved interstitially in fcc austenite

Focus on Steel





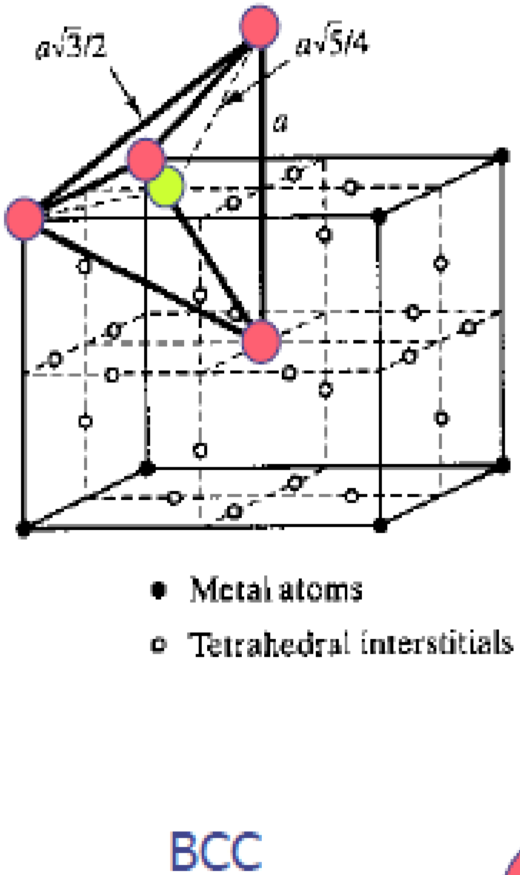
Interstitial sites:

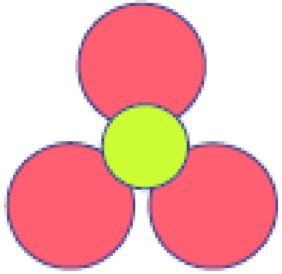
tetrahedral sites radius= 0.028 nm	fcc:	**octahedral** sites radius= 0.052 nm
tetrahedral sites radius= 0.036 nm	bcc:	**octahedral** sites radius= 0.019 nm

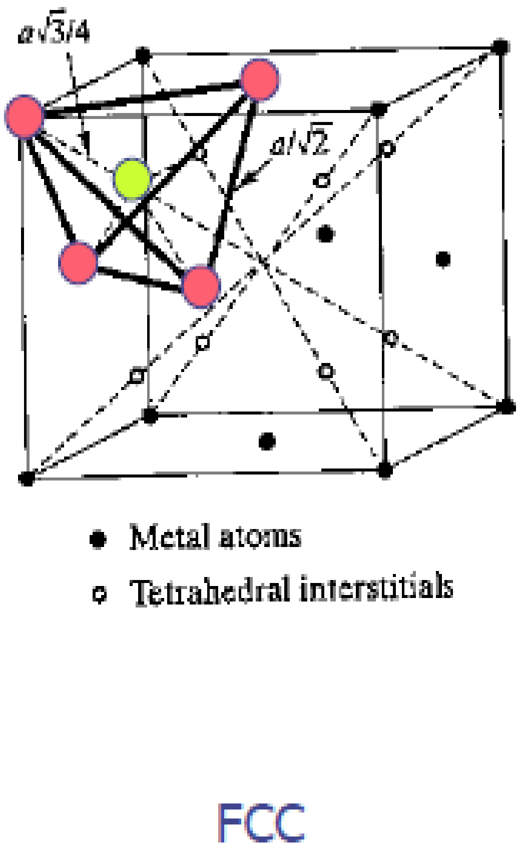
Carbon atom radius = 0.08 nm.

Focus on Steel

Interstitial Sites Tetrahedral

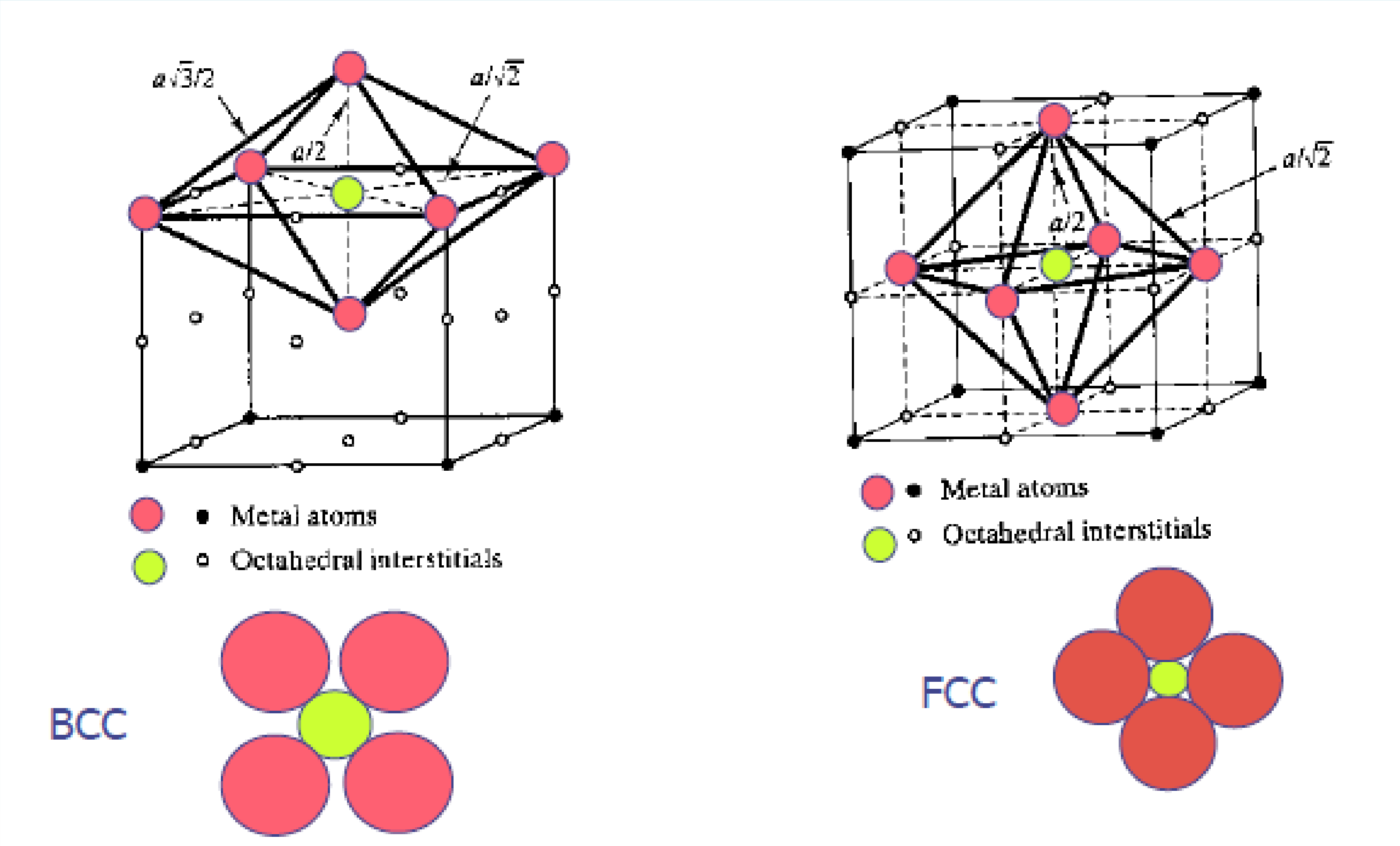






Focus on Steel

Interstitial Sites Octahedral



STEELS – There are so many

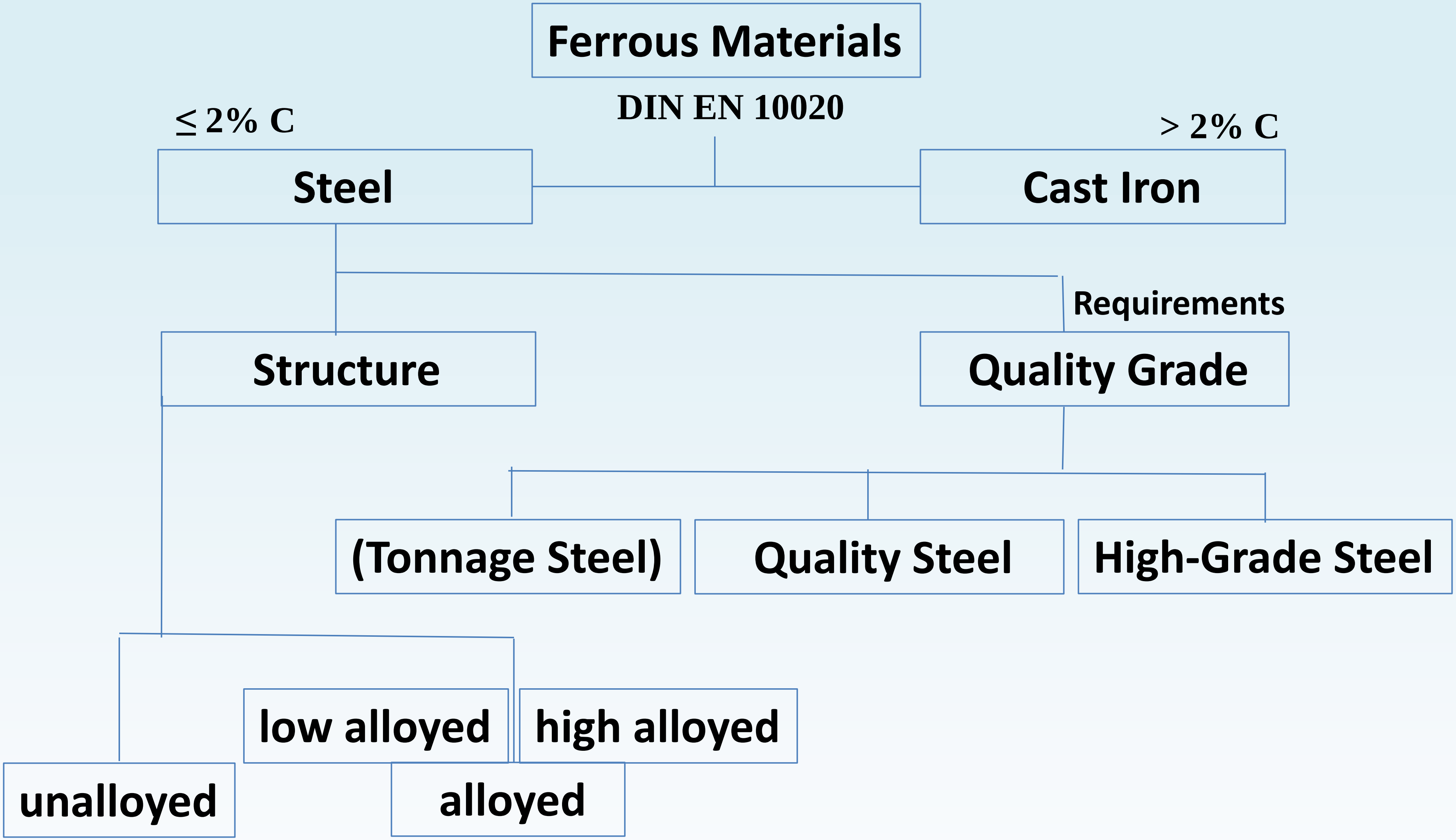
USAGE

Deep drawing steel	Low carbon steel strip with a microstructure to enable it to be extensively pressed or drawn without tearing or failure
Silicon steel	Another term for electrical steel - steel with particular electrical and magnetic properties that makes it especially suited to use in cores of electrical transformers, electrical motors, generators etc
Stainless steel	An alloy of carbon and iron that has a minimum chromium content of 10.5 percent
Structural steel	Construction material formed with a specific shape or cross section certain; it complies with standards of chemical composition and mechanical property requirements
Tool steel	Carbon and alloy steels that have high resistance to abrasion. They are well suited to the manufacture of tools

STEELS – There are so many
Composition

Austenitic steel	Austenitic steels have austenite as their primary phase (face centered cubic crystal). These are alloys containing chromium and nickel (sometimes manganese and nitrogen)
Ferroalloy	Alloy of iron with high proportion of an element such as nickel, chromium, molybdenum, vanadium, etc that used in the production of steel
Interstitial-free	Interstitial-free (IF) steels have few solute interstitial elements, such as carbon and nitrogen. These interstices can be sources of strain and may result in brittleness
Killed steel	Steel that has its oxygen content reduced - typically through addition of aluminium. Hence the term aluminium killed
Mild steel	Low carbon steel - often also referred to as soft steel. Carbon content generally under 0.25%
Wrought iron	Iron that has a low carbon content (usually les than 0.15 per cent). Many traditional applications of wrought iron now use low carbon steel instead

Focus on Steel – Steel Qualities



Focus on Steel – Steel Qualities

Limit Values for Alloy Elements

Al	B	Bi	Co	Cr	Cu	La	Mn	Mo	Nb	Ni	Pb	Se	Si	Te	Ti	V	W	Zr	
0,3	0,00 08	0,1	0,3	0,3	0,4	0,1	1,65	0,08	0,06	0,3	0,4	0,1	0,6	0,1	0,05	0,1	0,3	0,05	%

Unalloyed Steels

No Alloy Element exceeds its Limit Value

Alloyed Steels

At least one Alloy Element exceeds its Limit Value

low alloyed

high alloyed

At least one Alloy Element exceeds 5%

Focus on Steel – Steel Qualities

Alloyed Steels

Stainless Steels:

Chromium ≥ 10,5 %

Carbon ≤ 1,2 %

passivated

by the high chromium content that is very chemically inert and resistant to corrosion

Focus on Steel – Steel Qualities

QUALITY STEELS

Specified requirements:

- ***TOUGHNESS***
- ***WELDABILITY***
- ***FORMABILITY***

by:

- ***Fine-grained microstructure***

- ***Purity requirements:***

phosphorus and sulphur < 0.045%

HIGH-GRADE STEELS

Higher specified requirements:

- ***HIGHER STRENGTH VALUES***
- ***SUITABLE FOR TARGETED HEAT TREATMENT:***

especially:

- ***Hardening & Tempering***

Improved purity by special manufacturing processes:

phosphorus and sulphur < 0.025%

Focus on Steel – Steel Qualities

NOTE

HIGH-GRADE STEELS $\neq$ **STAINLESS STEELS**

CARBON STEELS

American Iron and Steel Institute

These are steels in which the main interstitial alloying constituent is

carbon in the range of 0.12–2.0%.

The American Iron and Steel Institute (AISI) defines carbon steel as the following:

"Steel is considered to be carbon steel when no minimum content is specified or required for

- **chromium,**
- **cobalt,**
- **molybdenum,**
- **nickel,**
- **niobium**
- **titanium,**
- **tungsten,**
- **Vanadium**
- **Zirconium**

or any other element to be added to obtain a desired alloying effect;

when the specified minimum for copper does not exceed 0.40 percent;

or when the maximum content specified for any of the following elements does not exceed the percentages noted:
manganese 1.65, silicon 0.60, copper 0.60."

Focus on Steel – Steel Qualities

Literature

1. Verhoeven, John D. *Steel Metallurgy for the Non-Metallurgist*. American Society for Metals, (2007), ISBN 9780871708588
2. Maranian, Peter. *Reducing Brittle and Fatigue Failures in Steel Structures*, New York: American Society of Civil Engineers, (2009), ISBN 978-0-7844-1067-7