Iron and steel

Applications:

Cutting tools, pressure vessels, bolts, hammers, gears, cutlery, jet engine parts, car bodies, screws, concrete reinforcement, 'tin' cans, bridges…

Why?

- **Ore is cheap and abundant**
- **Processing techniques are economical (extraction, refining, alloying, fabrication)**
- **High strength**
- **Very versatile metallurgy – a wide range of mechanical and physical properties can be achieved, and these can be tailored to the application**

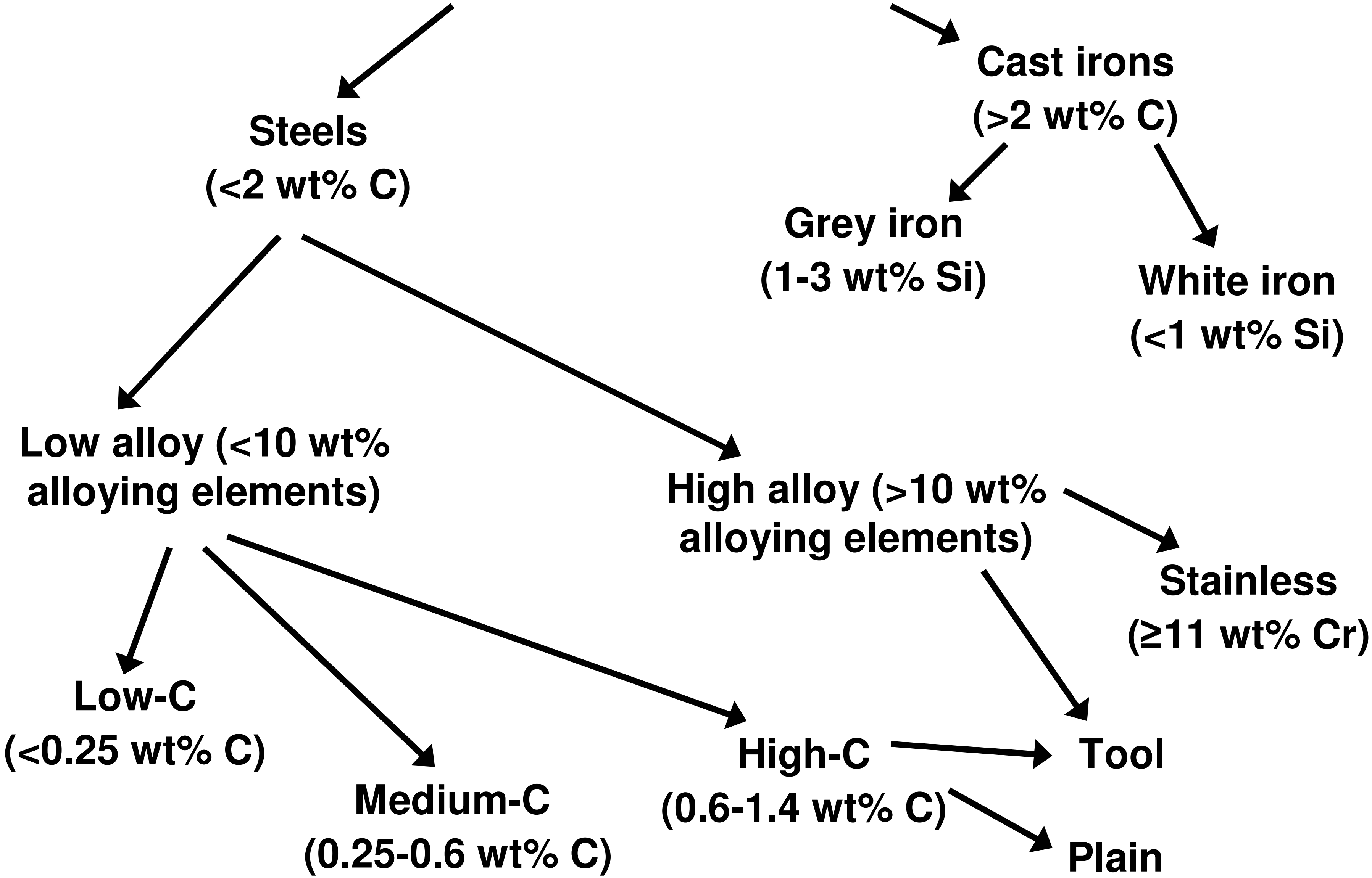
Disadvantages:

- **Low corrosion resistance (use e.g. titanium, brass instead)**
- **High density: 7.9 g cm^{-3} (use e.g. aluminium, magnesium instead)**
- **High temperature strength could be better (use nickel instead)**

→ **Basic distinction between ferrous and non-ferrous alloys:**

- **Ferrous metals are ‘all-purpose’ alloys**
- **Non-ferrous metals used for niche applications, where properties of ferrous metals are inadequate**

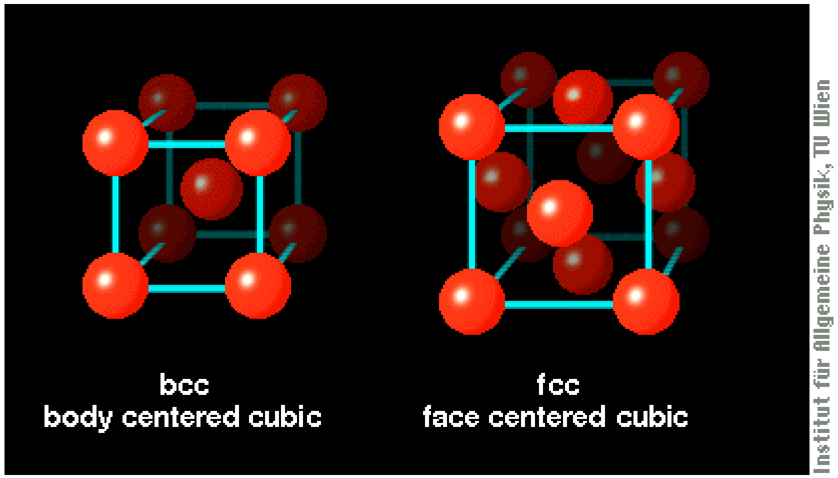
Classification of ferrous alloys



Steel metallurgy

Iron is allotropic / polymorphic i.e. exhibits different crystal structures at different temperatures

Most importantly: bcc ↔ fcc transformation at 912°C (for pure iron)

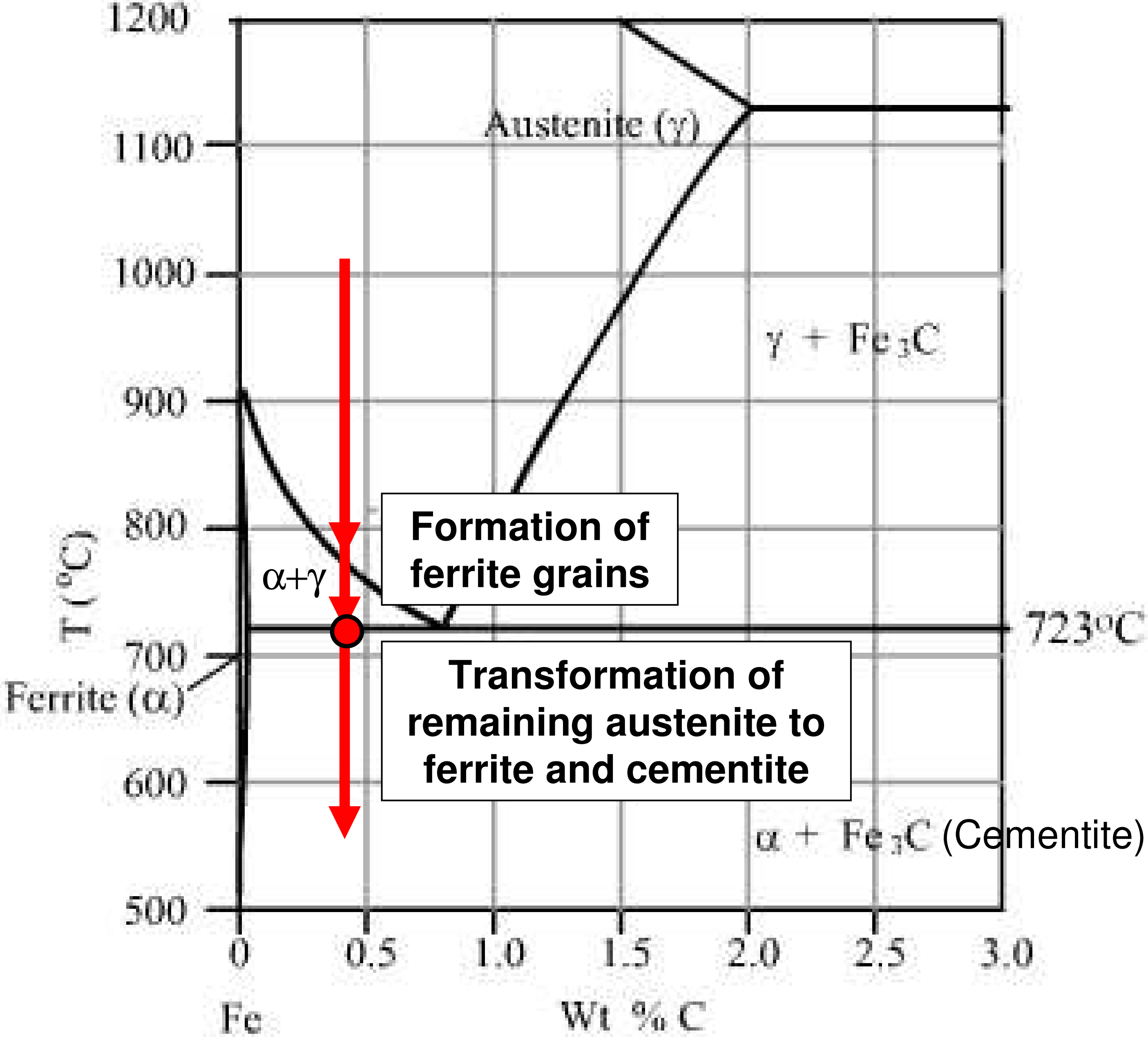


Solubility of carbon in ferrite (α-iron, bcc): 0.02 wt%

austenite (γ-iron, fcc): 2.1 wt%

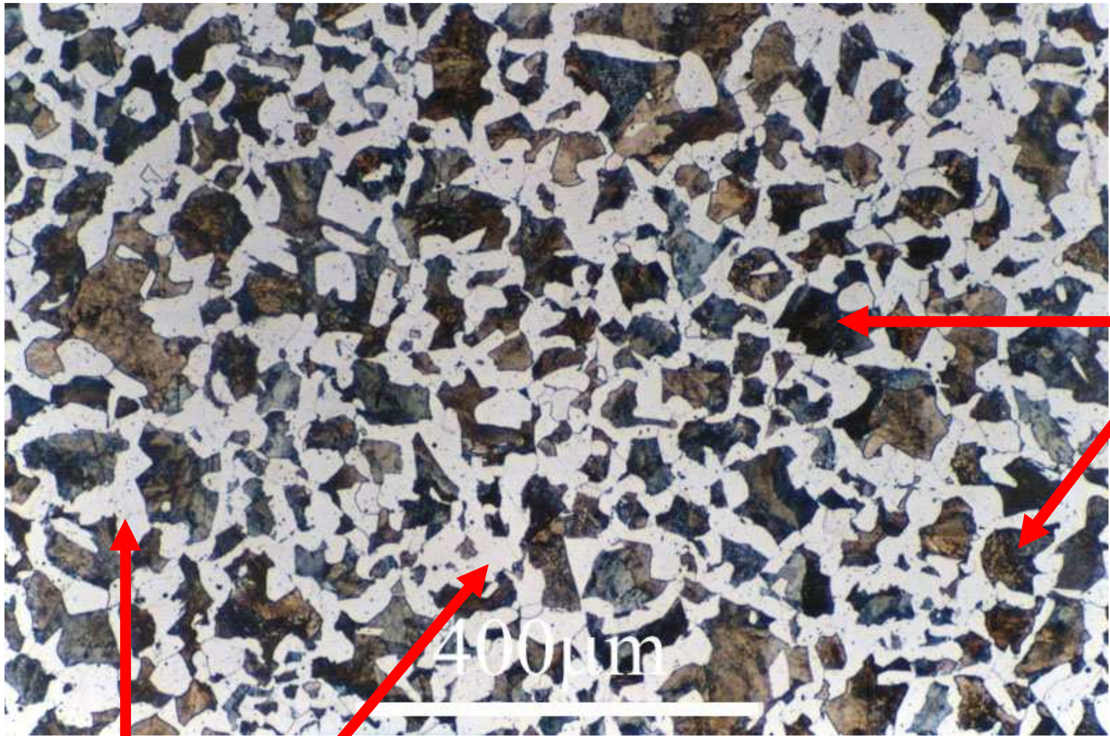
What happens to carbon when crystal structure transforms from fcc to bcc?

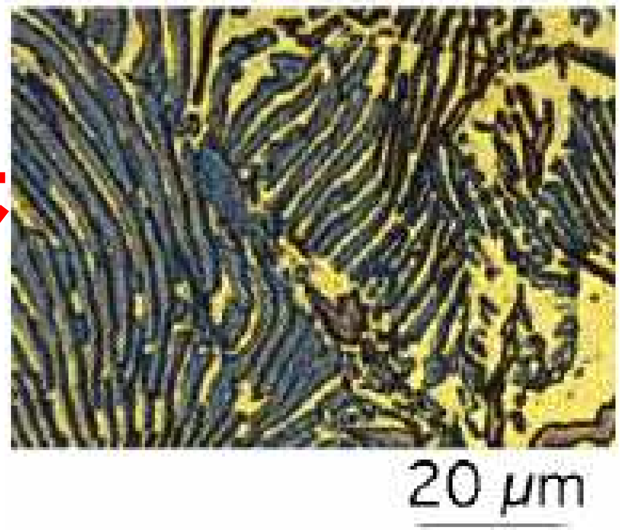
→ Fundamental issue in metallurgy of low alloy steels



1200
1100
1000
900
800
700
600
500
T (°C)
Austenite (γ)
γ + Fe3C
Formation of ferrite grains
α+γ
723°C
Ferrite (α)
Transformation of remaining austenite to ferrite and cementite
α + Fe3C (Cementite)
0
0.5
1.0
1.5
2.0
2.5
3.0
Fe
Wt % C

Fe 0.4wt% C





400 μm

Ferrite + cementite (Pearlite)

Ferrite

Also see
http://www-g.eng.cam.ac.uk/mmg/teaching/typd/index.html
and Callister 9.18 for good descriptions of the evolution of steel microstructure during cooling

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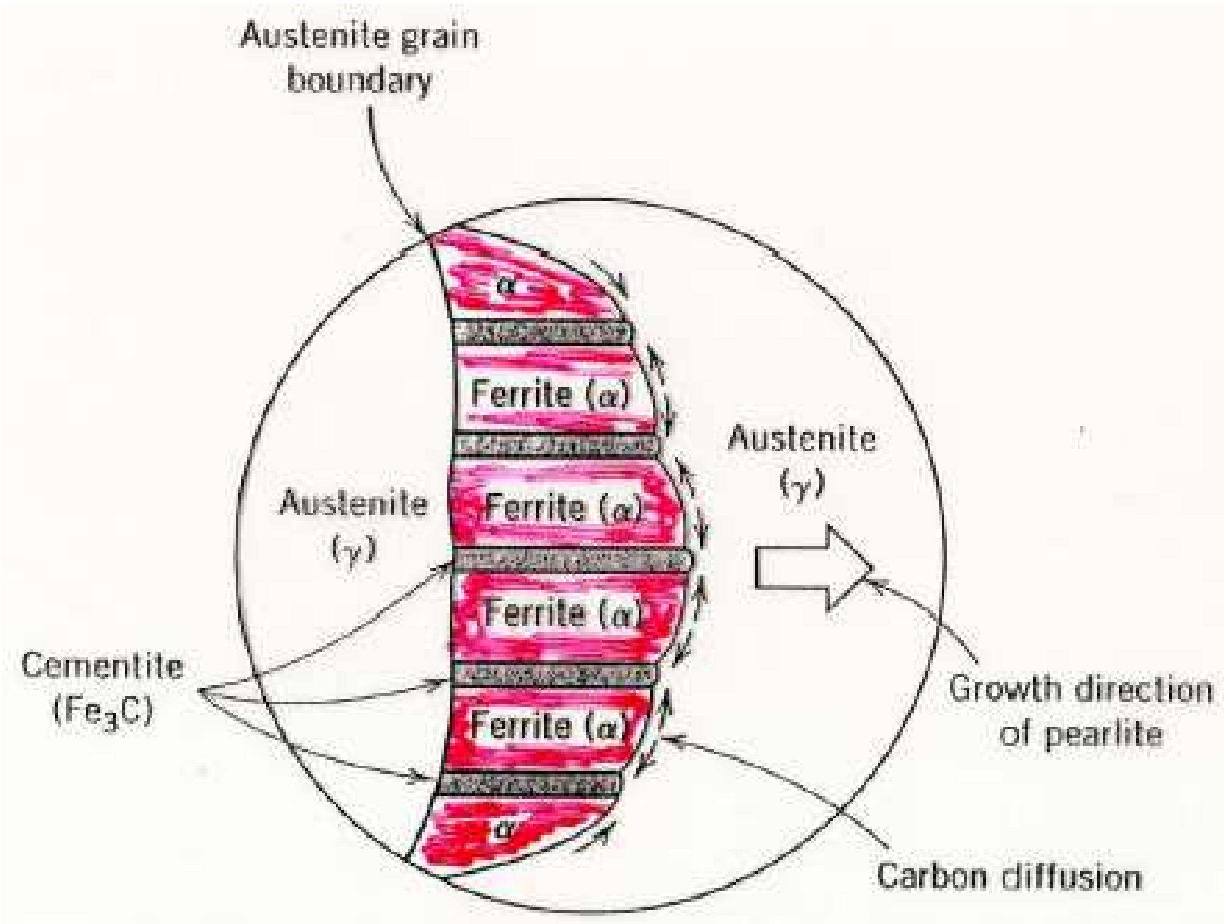
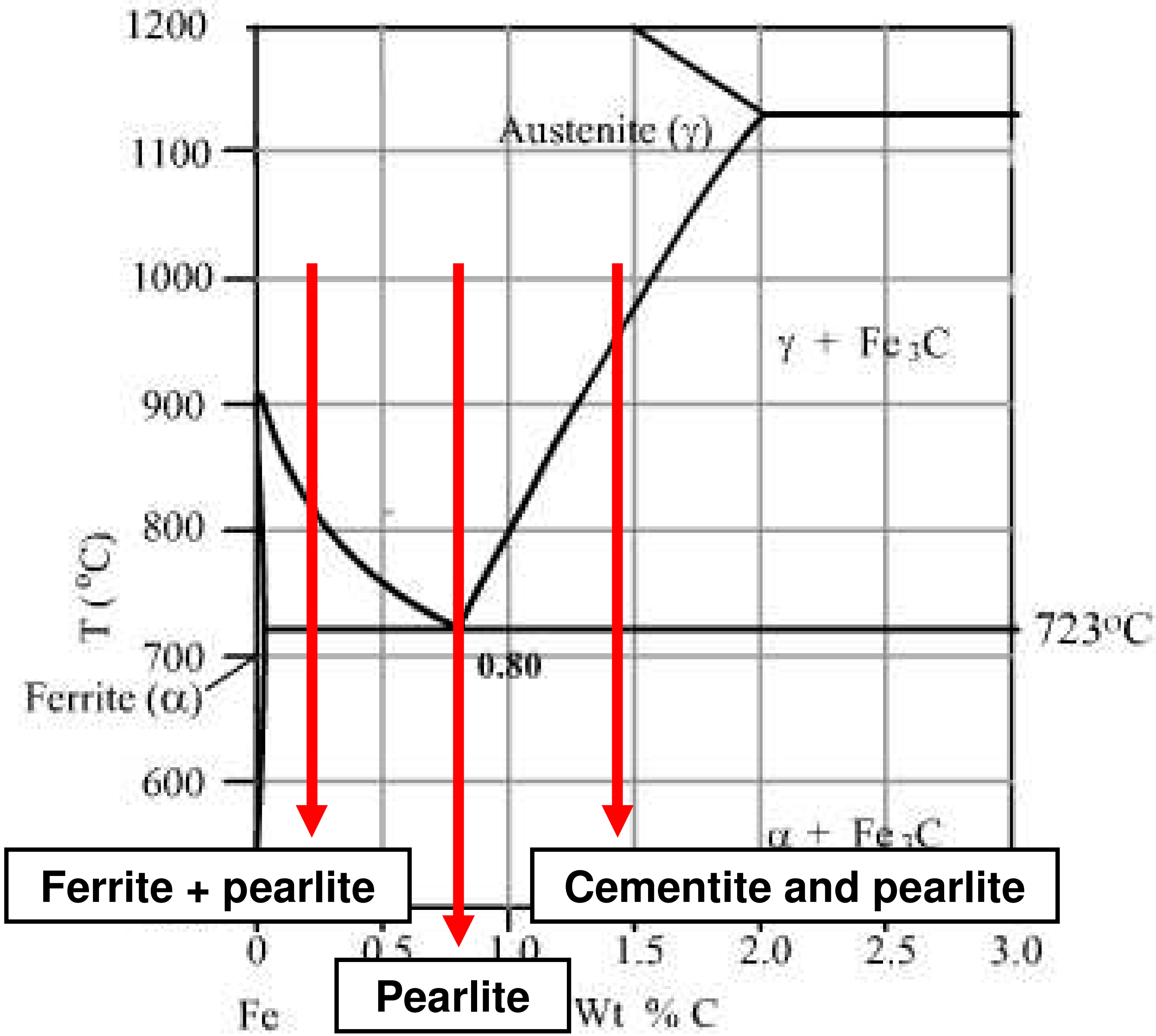
Pearlite

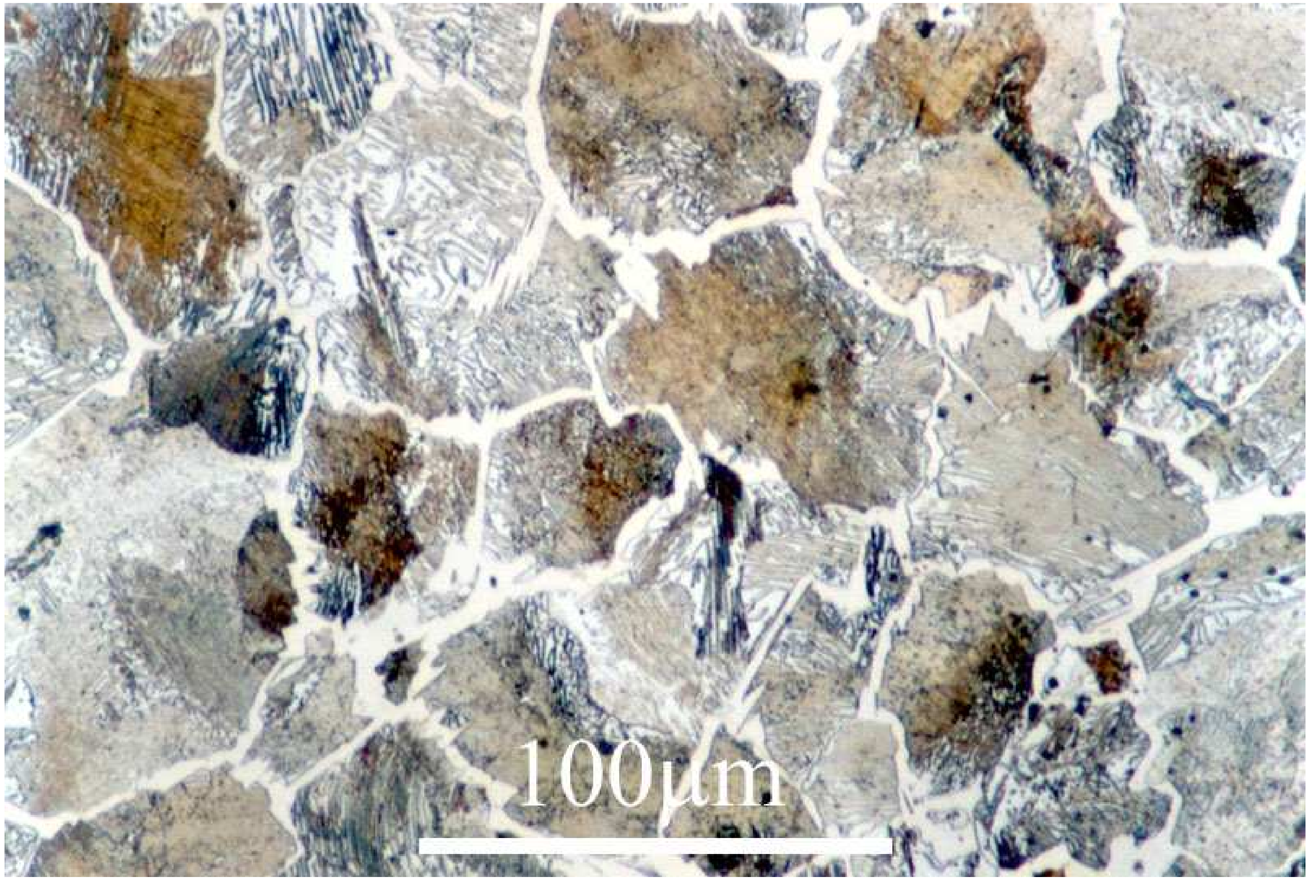
NB Pearlite is a MIXTURE of phases (on a very fine scale)

Alternating layers of ferrite and cementite formed simultaneously from the remaining austenite when temperature reaches 723°C





1200
1100
1000
900
800
700
600
T (°C)
Austenite (γ)
γ + Fe3C
723°C
0.80
Ferrite (α)
α + Fe3C
Ferrite + pearlite
Cementite and pearlite
Pearlite
0
0.5
1.0
1.5
2.0
2.5
3.0
Fe
Wt % C



Fe 1.3 wt% C: Cementite precipitates at austenite grain boundaries, remaining austenite is transformed into pearlite

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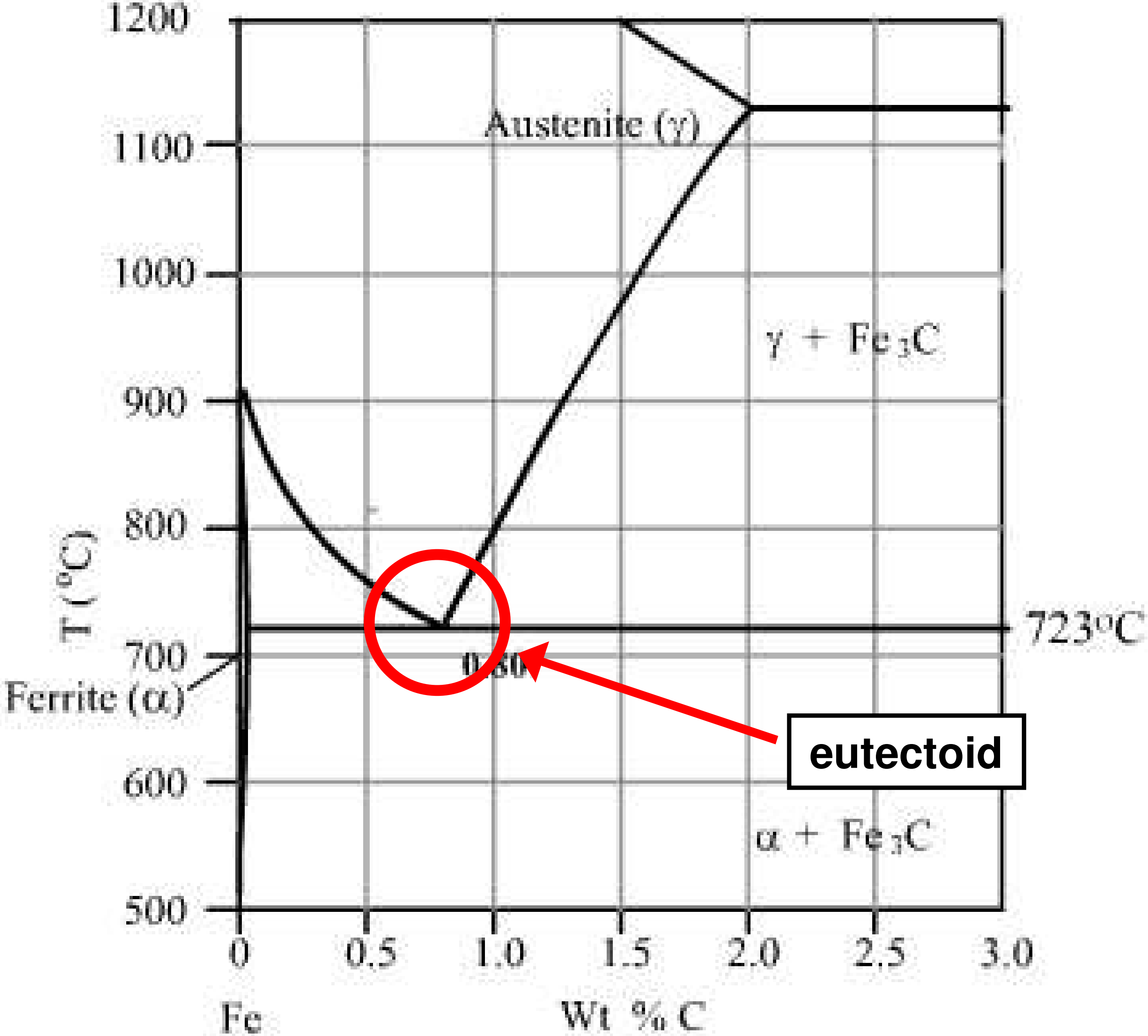
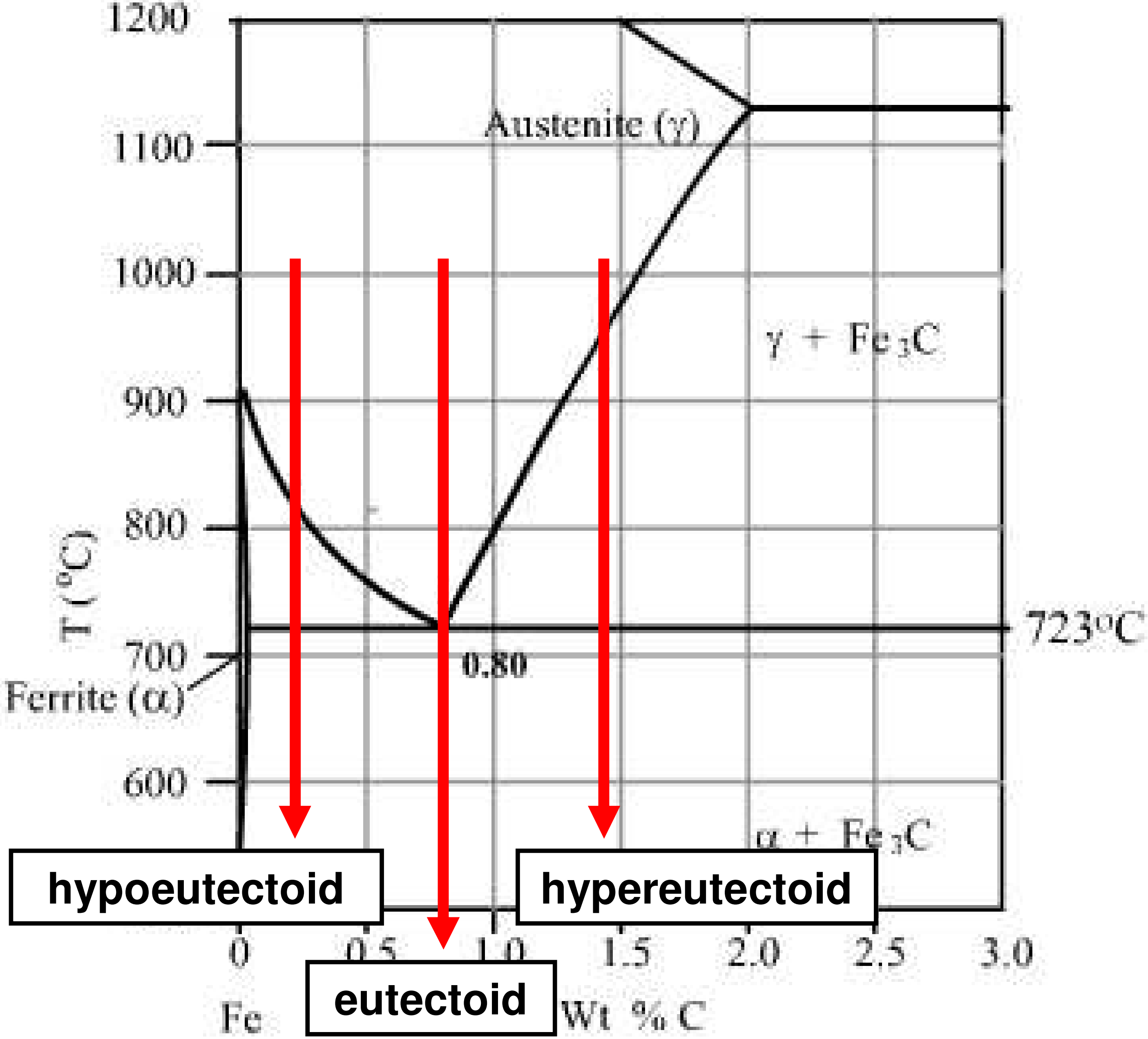
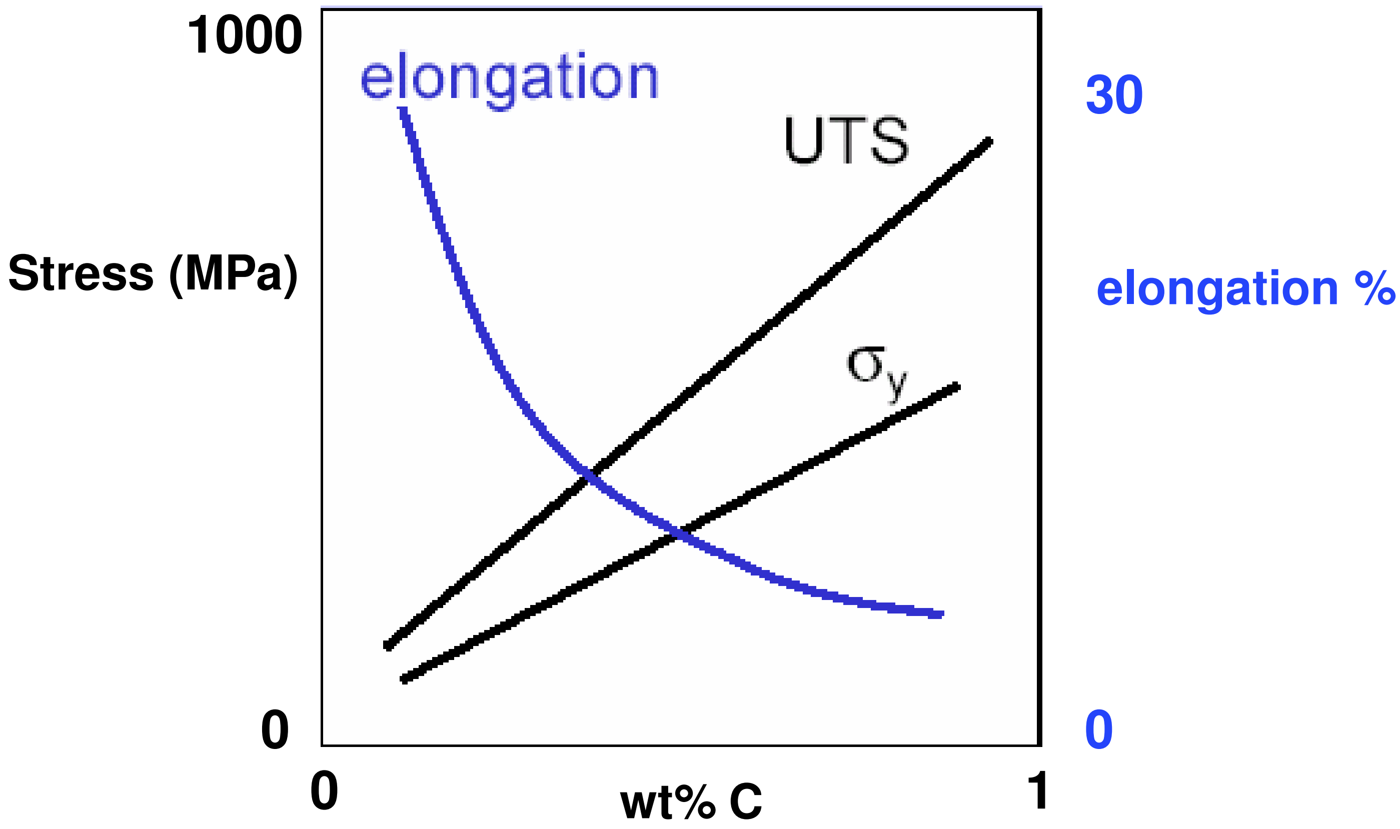


1200
1100
1000
900
800
700
600
500
T (°C)
Austenite (γ)
γ + Fe3C
723°C
0.80
Ferrite (α)
eutectoid
α + Fe3C
0
0.5
1.0
1.5
2.0
2.5
3.0
Fe
Wt % C


1200
1100
1000
900
800
700
600
T (°C)
Austenite (γ)
γ + Fe₃C
723°C
0.80
Ferrite (α)
α + Fe₃C
hypoeutectoid
eutectoid
hypereutectoid
0
0.5
1.0
1.5
2.0
2.5
3.0
Fe
Wt % C

Mechanical properties

Ferrite: soft and ductile **Cementite: hard and brittle**



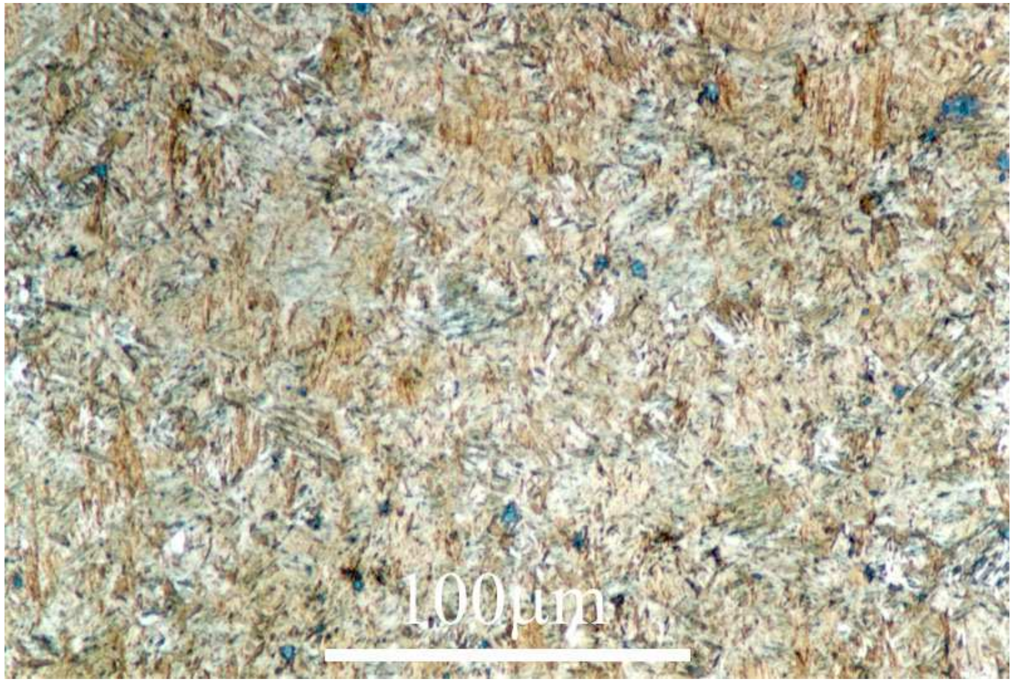
What happens during rapid cooling?

- **Phase diagrams only show stable phases that are formed during slow cooling**
- **If cooling is rapid, the phase diagram becomes invalid and metastable phases may form**
- **In the case of steel, the formation of ferrite and cementite requires the diffusion of carbon out of the ferrite phase. What happens if cooling is too rapid to allow this?**

➡ **The crystal lattice tries to switch from fcc (austenite) to bcc (ferrite). Excess carbon → distorted body-centred lattice → MARTENSITE**

Martensite (α')

- **Distorted bcc lattice**
- **Non-equilibrium carbon content**
- **Forms plate-like or needle-shaped grains**



Fe, C 2, Mn 0.7 (wt%)

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Martensite

- **Hard and brittle**
- **Applications: crankshafts, spanners, high-tension bolts**
- **In general too brittle to be useful, BUT if tempered can be used to produce optimum steel microstructure**

Tempering

- **Heat treatment of martensite carried out at 200-600℃ → allows C atoms to diffuse out of martensite**
- **Result:**

$$\alpha' \rightarrow \alpha + Fe_3C$$

- **Fe_3C present as uniform distribution of fine, round precipitates → high strength and toughness**

→ **QUENCHED AND TEMPERED steels**

Producing quenched and tempered steels

- Critical cooling rate for martensite formation depends on concentration of alloying elements (e.g. C, Mn, Cr, Ni). Alloying elements delay the formation of ferrite and pearlite → increase chances for martensite formation
- Critical cooling rate defines concept of HARDENABILITY (i.e. ease of martensite formation)
- Component thickness is an important parameter
  - ❑ Medium carbon steels generally used in quenched and tempered condition, high-carbon steels almost always:

    Applications: chisels, hammers, drills, cutting tools, springs…
  - ❑ Quenching and tempering not possible for low carbon steels → microstructure = ferrite + pearlite

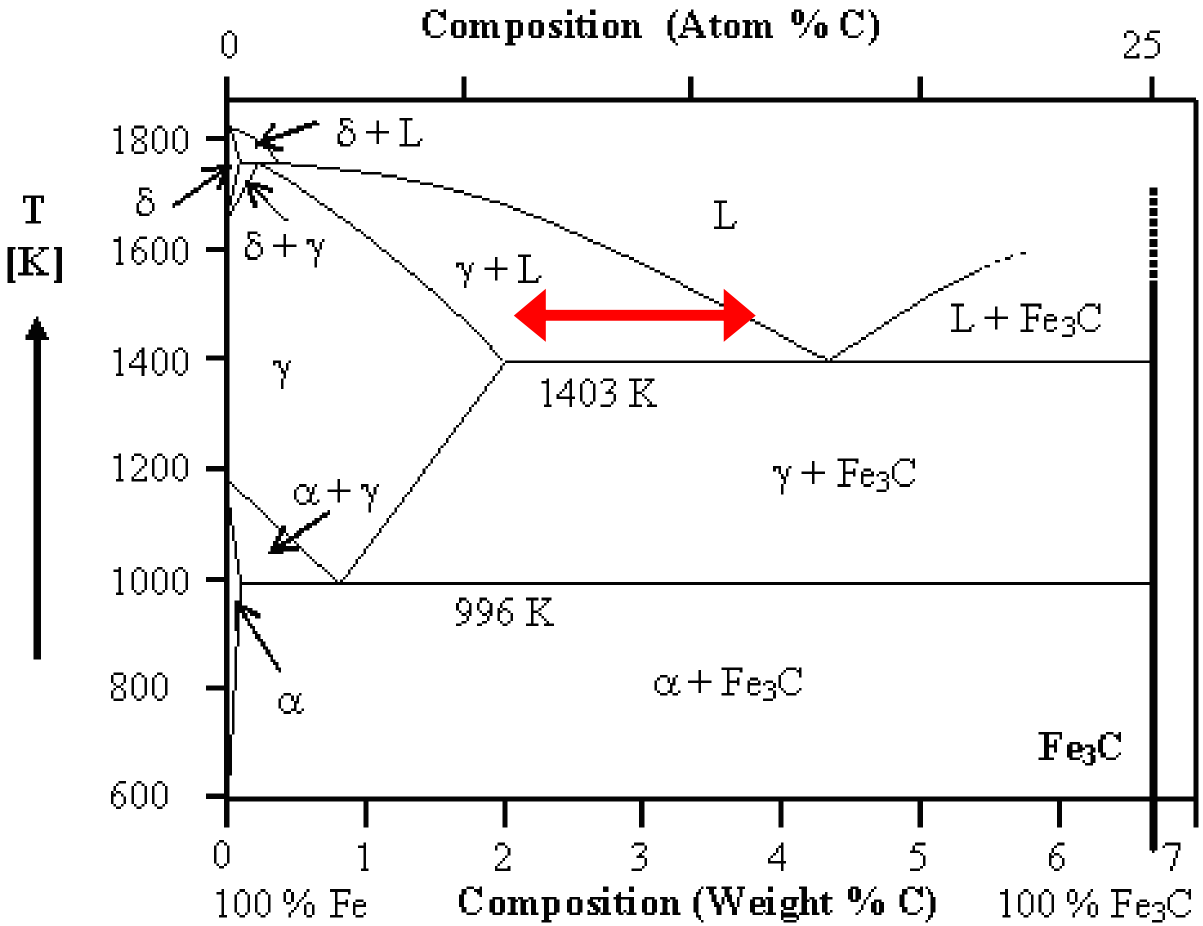
    Applications: car panels, bridges, pipes…

Stainless steels

- Definition: > 11 wt% Cr. Ni, Mn may also be present
- Cr → adherent Cr_2O_3 film → protection against corrosion and oxidation
- Most stainless steels are austenitic (alloying elements stabilise γ phase down to room T)
- Austenitic stainless steel is non-magnetic → useful as quick test
- Ferritic and martensitic stainless steels also available → increases range of mechanical properties available for specific applications (Corrosion resistance not as good as for austenitic stainless steel)

Cast Iron

High carbon content → low melting point



Cast Iron

- Cheap
- Low m.p. → can produce complex parts quickly and easily through sand casting
- BUT brittle

Two types:

- Grey iron: Fe + C (graphite)

  Formation of graphite rather than cementite promoted through high C and Si content, slow solidification rate
- White iron: Fe + Fe_3C

Grey cast iron

- Among least expensive metallic materials
- High fluidity → can cast complex shapes
- Graphite flakes → high damping capacity and good machineability → used e.g. as base structure for machines and heavy equipment
- BUT brittle due to shape of graphite flakes → nodular iron better

Fe, C 3.52, Si 3.26, Mn 0.47 (wt%)

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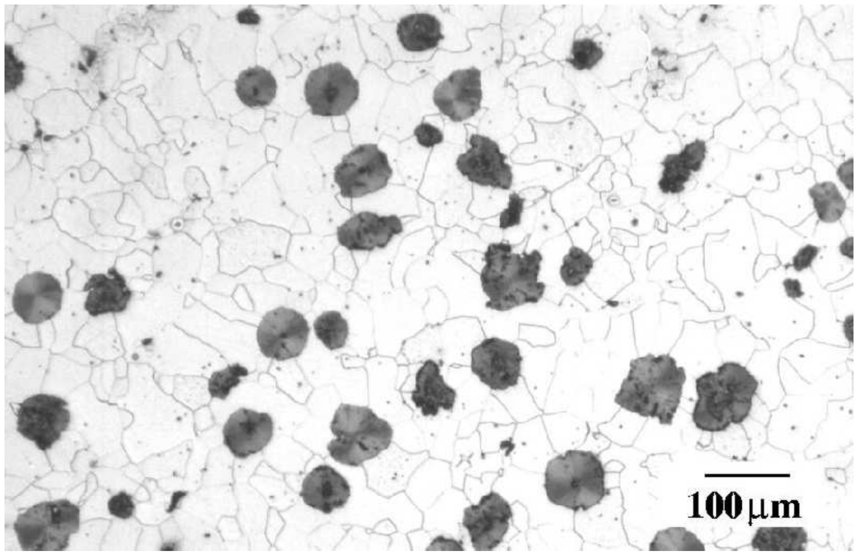
Ductile / Nodular cast iron

- Addition of Mg / Ce to grey iron → graphite forms as spheres rather than flakes → improved toughness
- Applications: valves, pump bodies, gears, crankshafts



Fe, C 3.2, Si 2.5, Mg 0.05 (wt%)

White cast iron

- **Exceptionally hard, but brittle and almost impossible to machine → used in very few applications e.g. rollers in rolling mills**
- **Used as intermediary in production of *malleable iron*: heat treatment at 800-900°C causes decomposition of cementite → graphite clusters. Resulting microstructure and properties similar to nodular iron. Typical applications: connecting rods, transmission gears, pipe fittings, flanges**