Metals III

Anne Mertens

Outline

- Introduction
  - Summary of previous lectures
  - Case study in controlling material structure: Fine grained casting
- Light alloys
- Carbon steels
- Alloy steels
- Production, forming and joining of metals

Introduction

Summary of previous lectures

Materials selection

- Aim: select the best material for a given application
- Many ≠ criteria must be taken into account
  - Physical properties (density, conductivity...)
  - Mechanical properties (yield stress, fatigue...)
  - Corrosion resistance
  - Bio-compatibility
  - Processability, formability
  - Cost
  - ...

Materials selection

- Aim: select the best material for a given application
- Many ≠ criteria must be taken into account

⇒ Need for a methodology

⇒ Need for database of materials properties

Data for metals

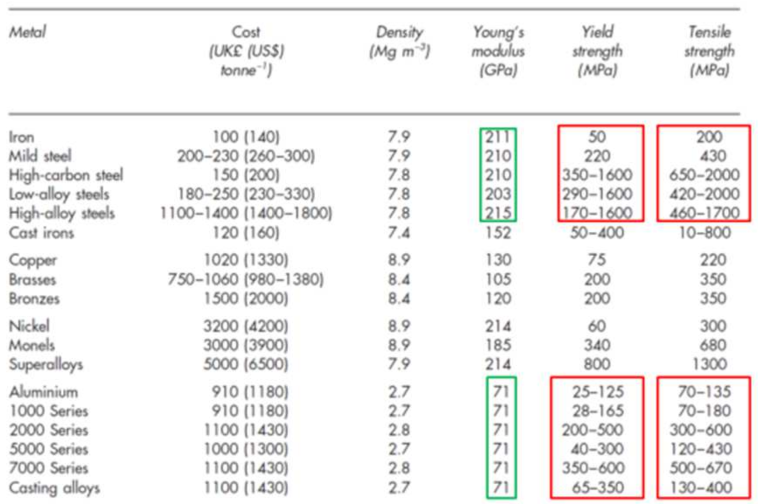


Table 1.6 Properties of the generic metals

Metal	*Cost (UK£ (US$) tonne^{-1})*	*Density (Mg m^{-3})*	*Young's modulus (GPa)*	*Yield strength (MPa)*	*Tensile strength (MPa)*
Iron	100 (140)	7.9	211	50	200
Mild steel	200–230 (260–300)	7.9	210	220	430
High-carbon steel	150 (200)	7.8	210	350–1600	650–2000
Low-alloy steels	180–250 (230–330)	7.8	203	290–1600	420–2000
High-alloy steels	1100–1400 (1400–1800)	7.8	215	170–1600	460–1700
Cast irons	120 (160)	7.4	152	50–400	10–800
Copper	1020 (1330)	8.9	130	75	220
Brasses	750–1060 (980–1380)	8.4	105	200	350
Bronzes	1500 (2000)	8.4	120	200	350
Nickel	3200 (4200)	8.9	214	60	300
Monels	3000 (3900)	8.9	185	340	680
Superalloys	5000 (6500)	7.9	214	800	1300
Aluminium	910 (1180)	2.7	71	25–125	70–135
1000 Series	910 (1180)	2.7	71	28–165	70–180
2000 Series	1100 (1430)	2.8	71	200–500	300–600
5000 Series	1000 (1300)	2.7	71	40–300	120–430
7000 Series	1100 (1430)	2.8	71	350–600	500–670
Casting alloys	1100 (1430)	2.7	71	65–350	130–400

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Structure-insensitive

vs

structure-dependent

Materials structure

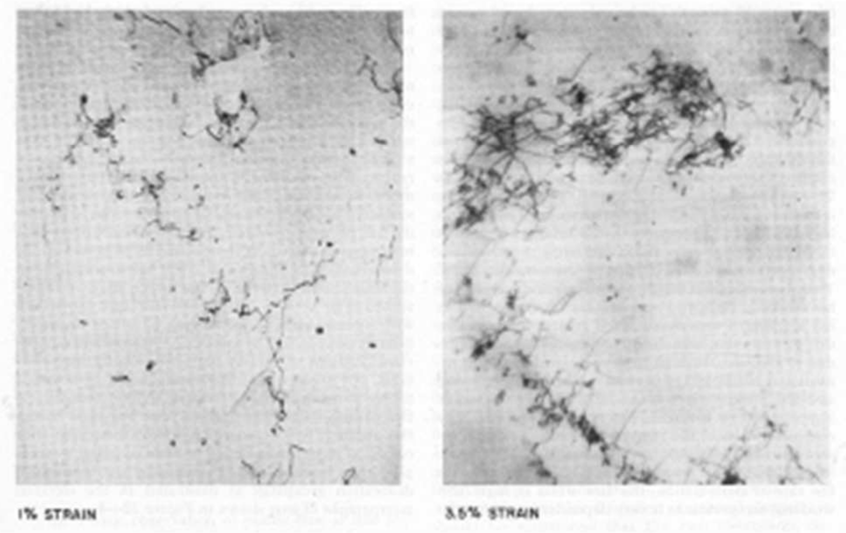
- Materials selection to fulfill desired properties
- Some properties of metals are **structure**-sensitive
  - Crystalline vs amorphous structure
  - Phases (solid solution, intermetallic compounds...)
  - Grain size and shape, grain and interphase boundaries
- How can we control the structure?
  - **Equilibrium** structure:
    by playing with the **chemical composition**
  - **Out-of-equilibrium** structure:
    by playing with phase transformations, plastic strain....

Materials structure

- How can we control the structure?
  - **Out-of-equilibrium** structure:
    by playing with phase transformations, plastic strain....

- Example 1: plastic deformation

  Creation and propagation of crystalline defects



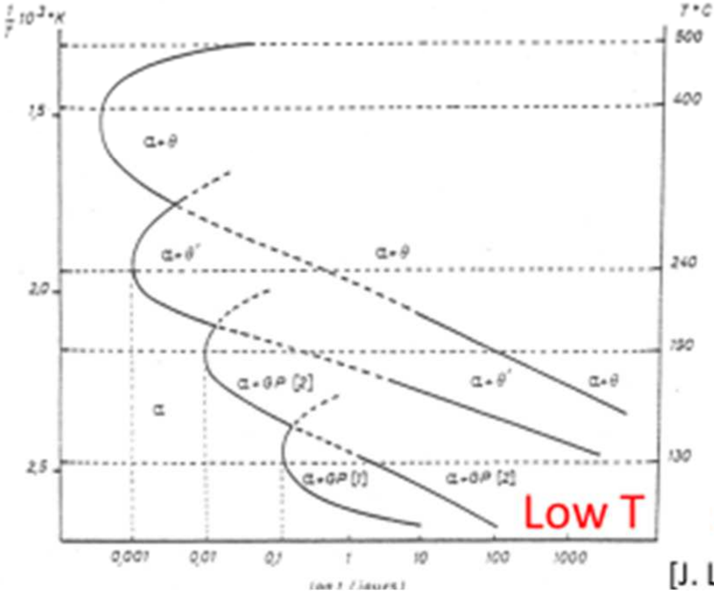
Dislocations density ↑
⇒ Entanglement
⇒ Dislocations glide more difficult
⇒ Strength ↑
⇒ **Work hardening**

[J. Lecomte-Beckers, Phys0904 "Physique des Matériaux"]

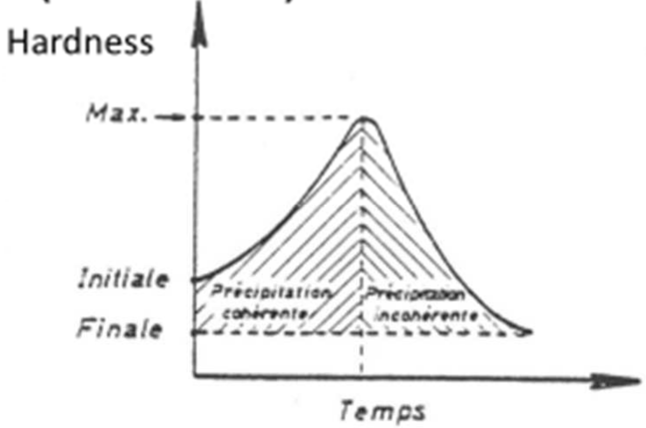
Materials structure

- How can we control the structure?
  - **Out-of-equilibrium** structure:
    by playing with phase transformations, plastic strain....
    - Example 2: Intermetallic compounds

Heat treatment to control the formation of Al_2Cu and obtain optimized properties (Hardness)



Low T



⇒ Small coherent precipitates

[J. Lecomte-Beckers, Phys0904 "Physique des Matériaux"]

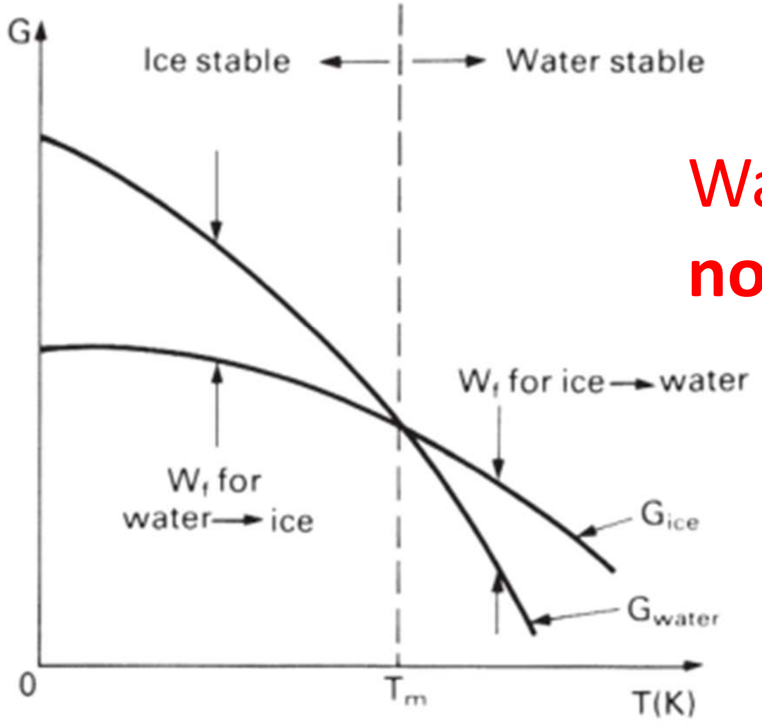
Background on structural change

- Is change **possible**? ⇒ Driving force

Water might **perhaps** solidify into ice

⇒ **Kinetics**

Driving force for solidification



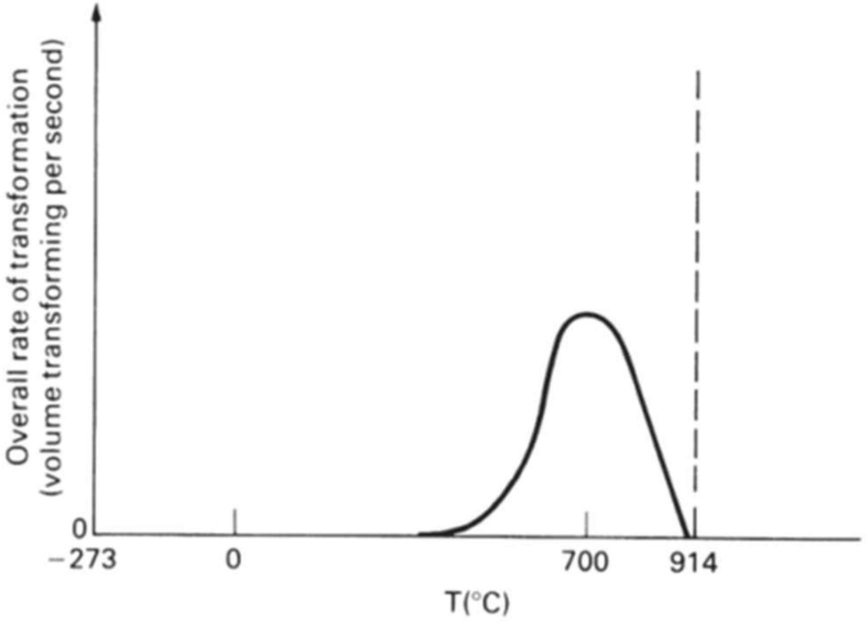
Water will **not** solidify

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Background on structural change

- Kinetics: What is the **speed** of change?
- Kinetics depend on the mechanisms
  - – Diffusion
  - – Displacement
  - – Nucleation
    - Homogeneous
    - Heterogeneous

Assume the pre-existence then growth of nuclei of the new phase



Overall rate of transformation depends on individual rates for nucleation and growth

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Introduction

Case study: Fine grained casting

Casting

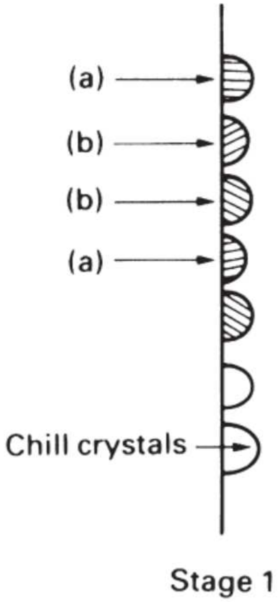
- Suitable for relatively complex shape
- Solidification structure? Grains?

[P. Nyssen, CRM]

[http://www.bluemaize.net/arts-crafts-sewing/metal-casting]

Casting

- Solidification structure? Grains?



Stage 1:

Small solid crystals nucleate on the cold walls of the mould
= "chill" crystals

$\Rightarrow$ Heterogeneous nucleation

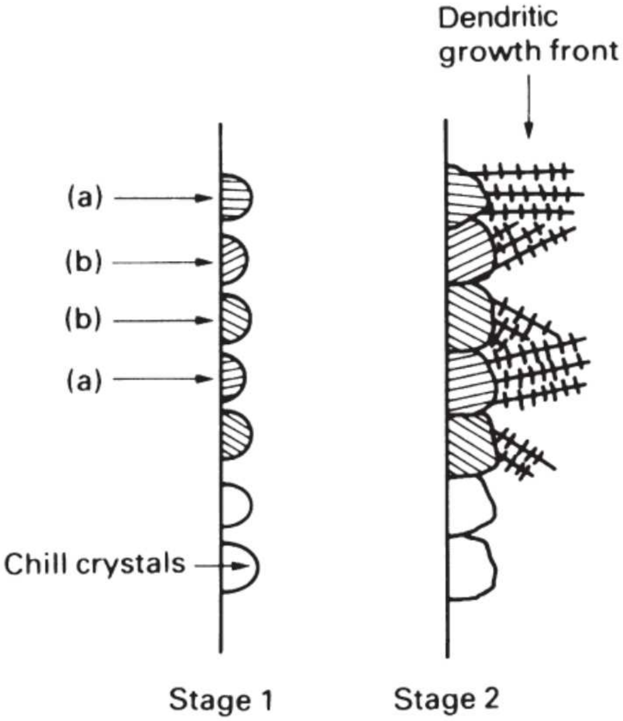
[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Casting

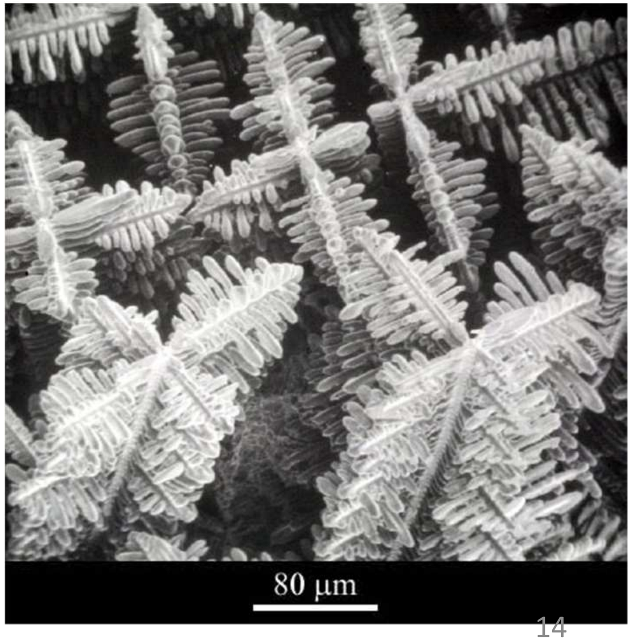
- Solidification structure? Grains?

Stage 2:

"Chill" crystals grow into the liquid
Common morphology in metals:
Dendrites



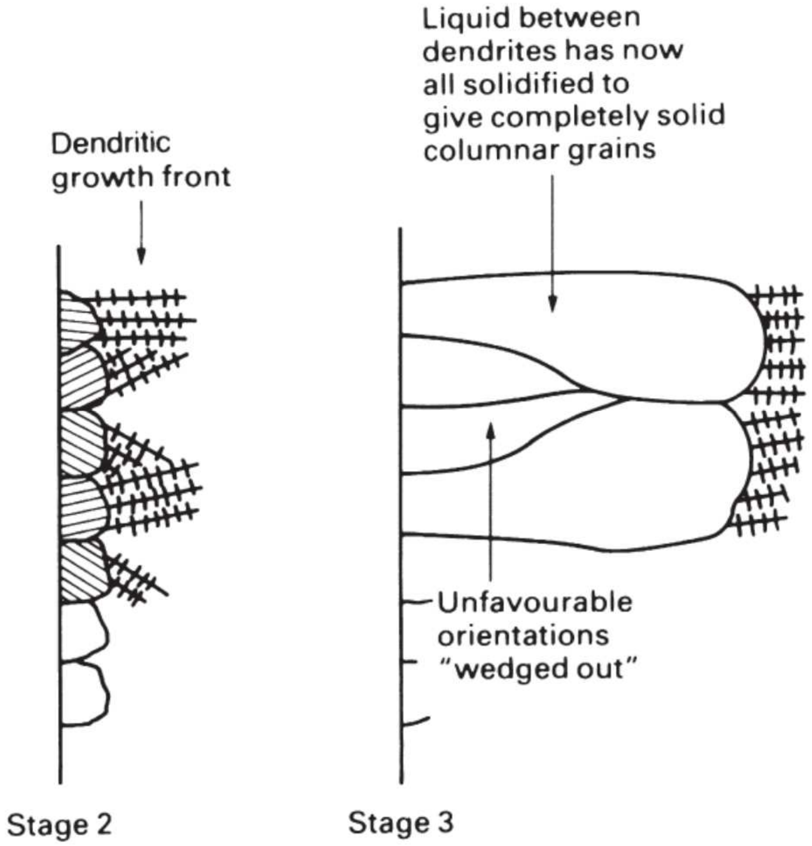
[M.F. Ashby and D.R.H. Jones,
Engineering Materials, vol. 2]



[https://www.doitpoms.ac.uk/tlplib/
solidification_alloys/dendritic.php]

Casting

- Solidification structure? Grains?



Stage 3:

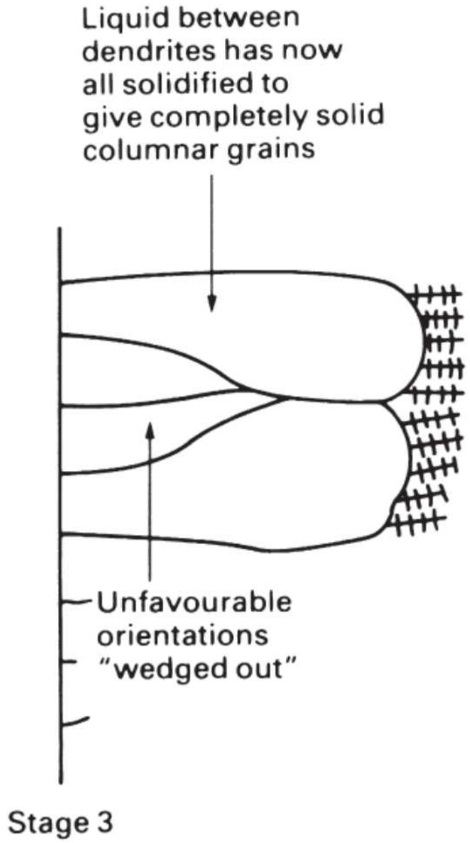
Dendrites keep growing
Their arms impinge against each other

$\Rightarrow$ **Columnar grains**

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Casting

- Solidification structure? Grains?



Columnar grains

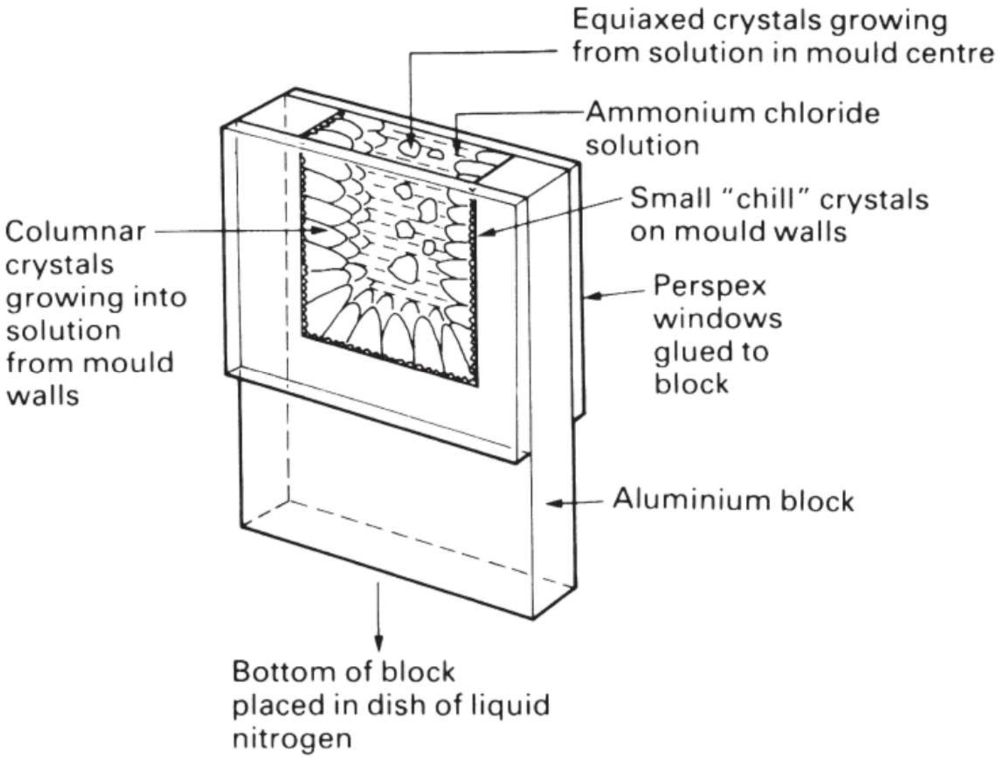
- Coarse structure: not favourable for mechanical properties
- Impurities or alloying elements get "pushed" ahead of the solidification front

$\Rightarrow$ **Segregation**

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Casting

- Solidification structure? Grains?



Stage 4:

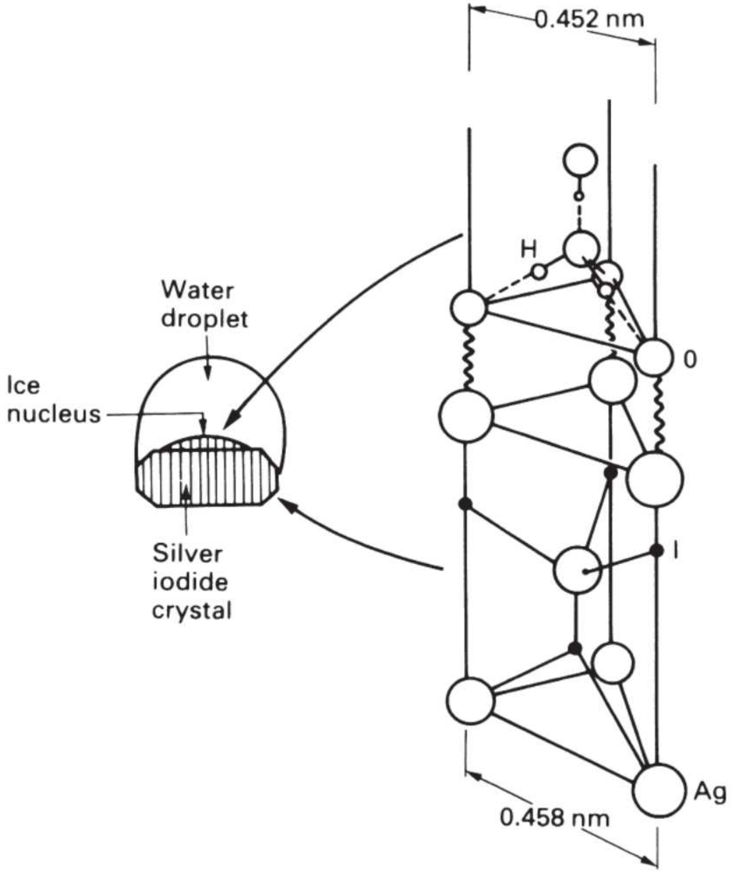
Crystals nucleate on "dirt" and grow in the melt centre

$\Rightarrow$ **Equiaxed grains**

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Casting

- How can we improve the solidification structure?



Use of **inoculants**
to favour equiaxed grain
structure throughout
the part

E.g.: AgI for ice

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Outline

- Introduction
- Light alloys
  - Magnesium, Aluminium, Titanium
- Carbon steels
- Alloy steels
- Production, forming and joining of metals

Light alloys

Alloys with density $\leq$ 4,5 kg/dm^3

Light alloys

- 14 metallic elements with density ≤ 4,5 kg/dm^3
- 3 are useful for structural applications

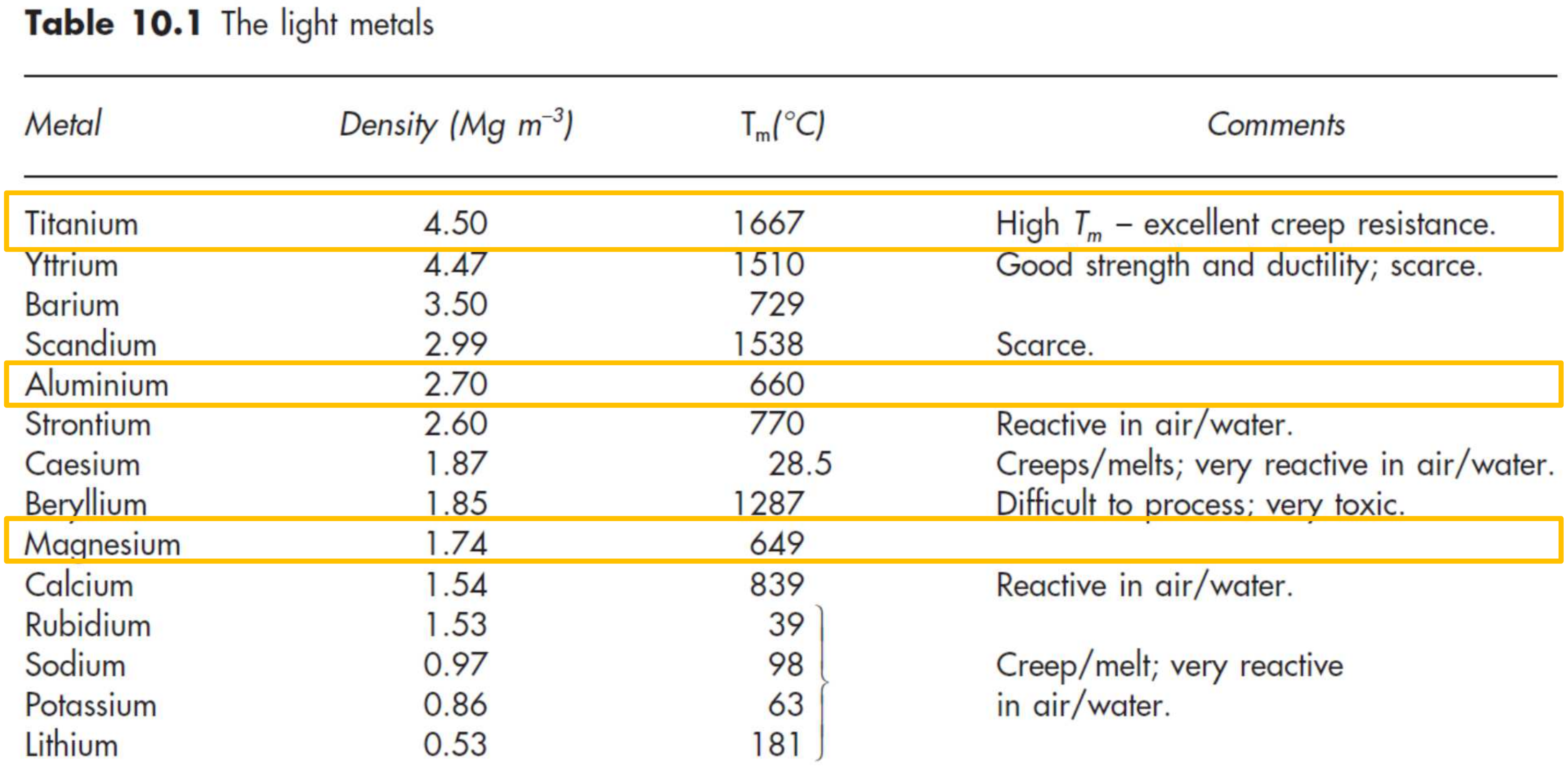


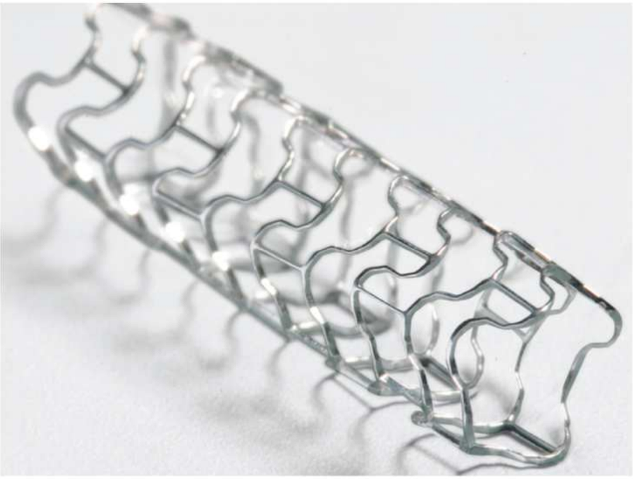
Table 10.1 The light metals

Metal	*Density (Mg m^{-3})*	T_m(°C)	*Comments*
Titanium	4.50	1667	High T_m – excellent creep resistance.
Yttrium	4.47	1510	Good strength and ductility; scarce.
Barium	3.50	729	
Scandium	2.99	1538	Scarce.
Aluminium	2.70	660	
Strontium	2.60	770	Reactive in air/water.
Caesium	1.87	28.5	Creeps/melts; very reactive in air/water.
Beryllium	1.85	1287	Difficult to process; very toxic.
Magnesium	1.74	649	
Calcium	1.54	839	Reactive in air/water.
Rubidium	1.53	39	Creep/melt; very reactive in air/water.
Sodium	0.97	98	
Potassium	0.86	63	
Lithium	0.53	181	

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Light alloys

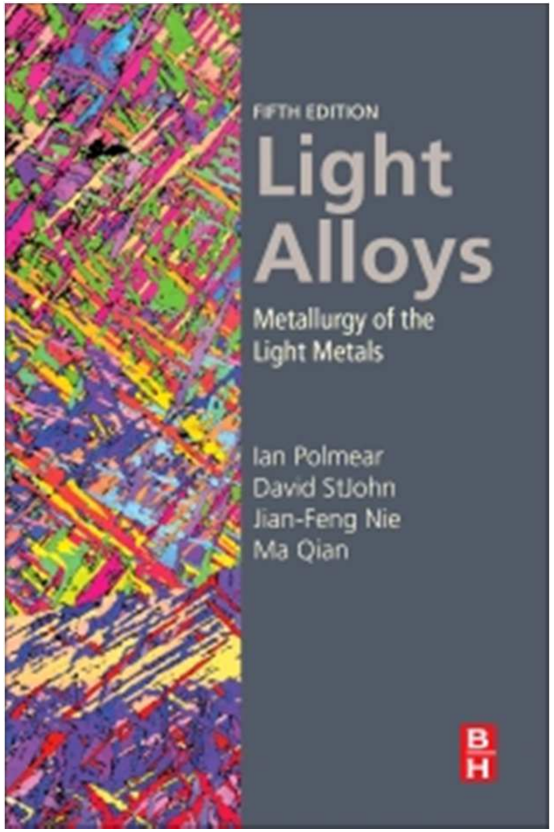
- Mg, Al and Ti alloys were 1st developed for aerospace and transportation
- Mg and Ti alloys are also widely used in biomedical applications
- Al is also used in packaging (beverage can...)



Mg bioabsorbable stent
[http://archiv.ethlife.ethz.ch/images/magnesiumstent-l.jpg]

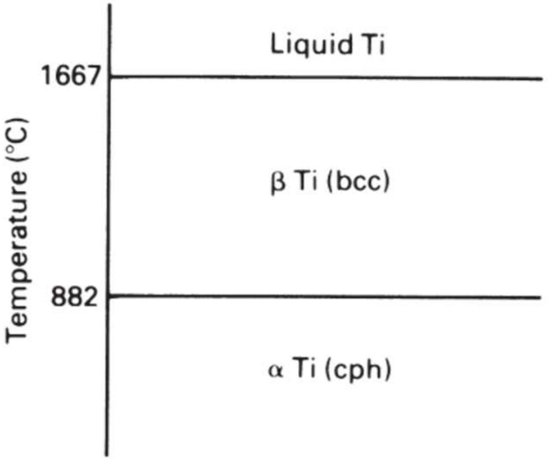
Light alloys

- A good reference:
  "Light alloys - metallurgy of ligh metals" by I. Polmear, D. StJohn, J.F. Nie and Ma Qian, (2017)
  Available from ULiege library
  of electronic resources



Light alloys

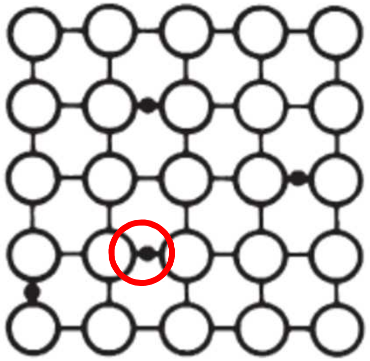
- 3 main strengthening mechanisms
  1. Solid solution hardening
  2. Age (or precipitation) hardening
  3. Work hardening
- + another mechanism in (some) Ti alloys:
  - Martensitic transformation



[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

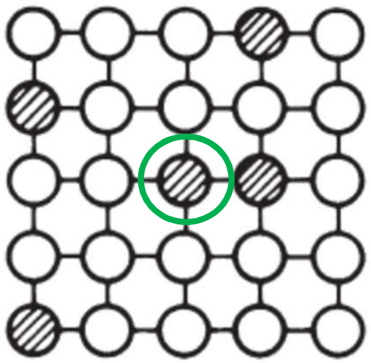
Solid solution strengthening (1)

- Alloying elements may be dissolved in the crystallographic lattice of the main element



Interstitial solution

e.g.: C in Fe



Substitutional solution

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Solid solution strengthening (2)

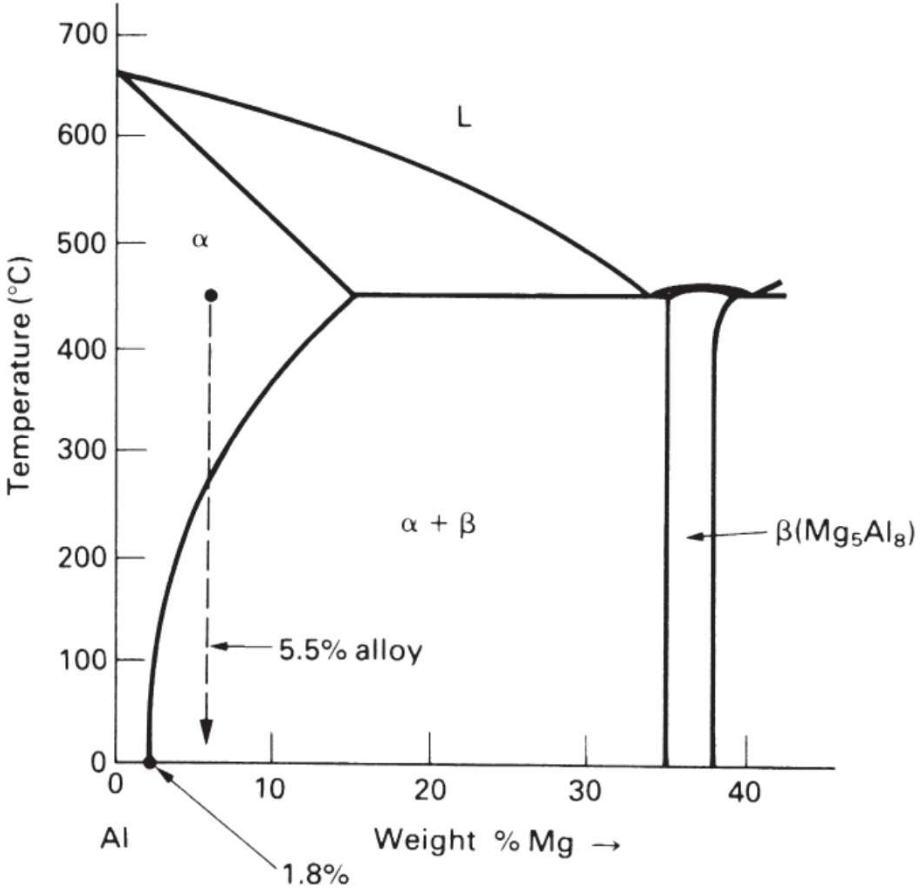
- Alloying elements may be dissolved in the crystallographic lattice of the main element
- Solute atoms ≠ solvent atoms
  - ≠ size, stiffness, charge...
  - Solute atoms cause lattice distortion and interact with dislocations, making dislocations glide more difficult:

$$\sigma_y \propto \varepsilon_s^{3/2} C^{1/2}$$

with *C*: solute concentration,
and ε_s : mismatch between solute and solvent atoms

Solid solution strengthening (3)

- 5xxx Al alloys (= Al-Mg alloys)



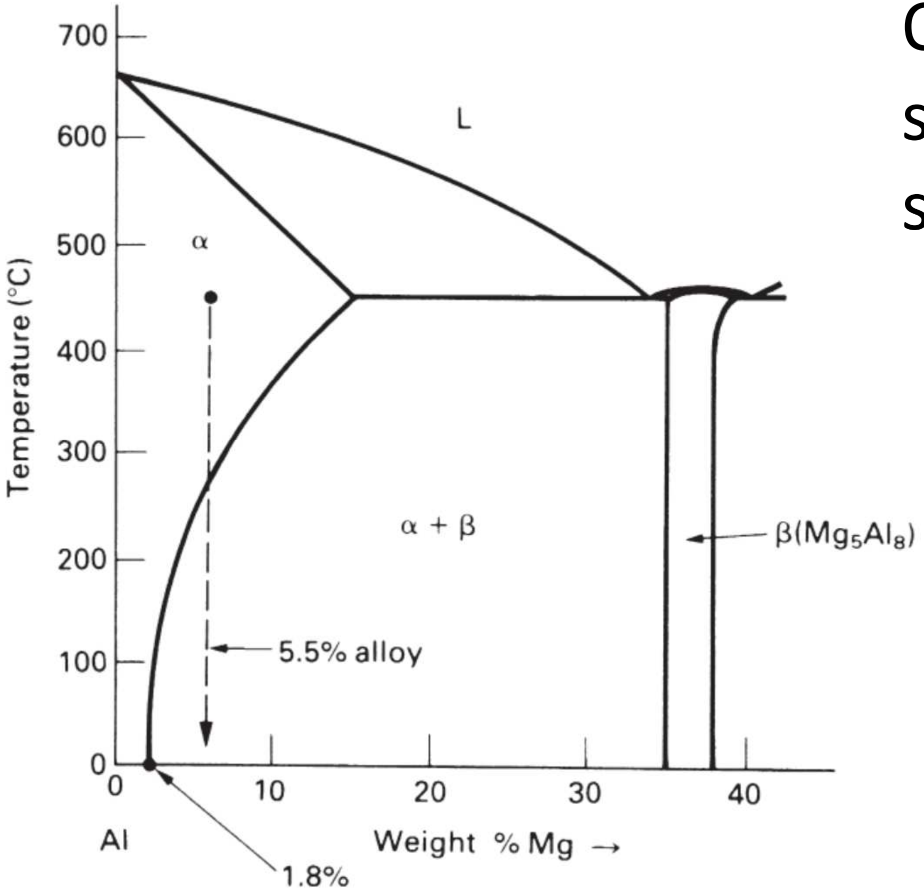
[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Obtention of a supersaturated solid solution up to 5,5 wt% Mg

1. Solution treatment at 450°C

Solid solution strengthening (4)

- 5xxx Al alloys (= Al-Mg alloys)



[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Obtention of a supersaturated solid solution up to 5,5 wt% Mg

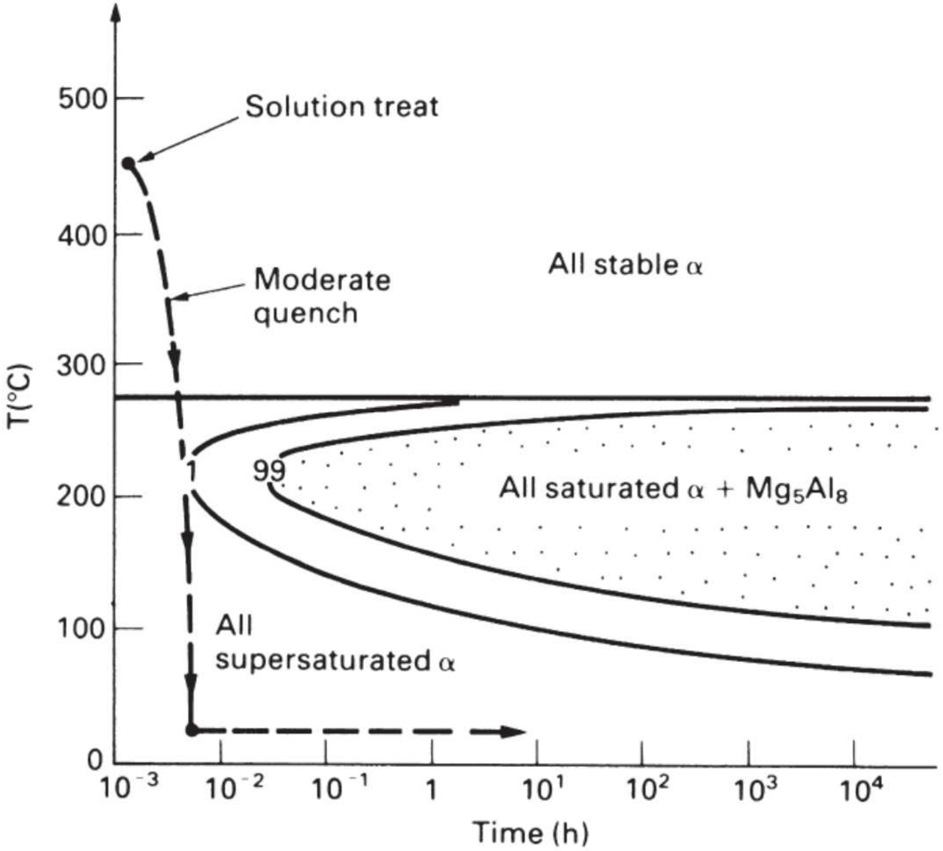
1. Solution treatment at 450°C
2. Rapid cooling down to R.T. (below 275°C)

Solid solution strengthening (5)

- 5xxx Al alloys (= Al-Mg alloys)

Obtention of a supersaturated solid solution up to 5,5 wt% Mg

1. Solution treatment at 450°C
2. Rapid cooling below 275°C



[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Solid solution strengthening (6)

- 5xxx Al alloys (= Al-Mg alloys)

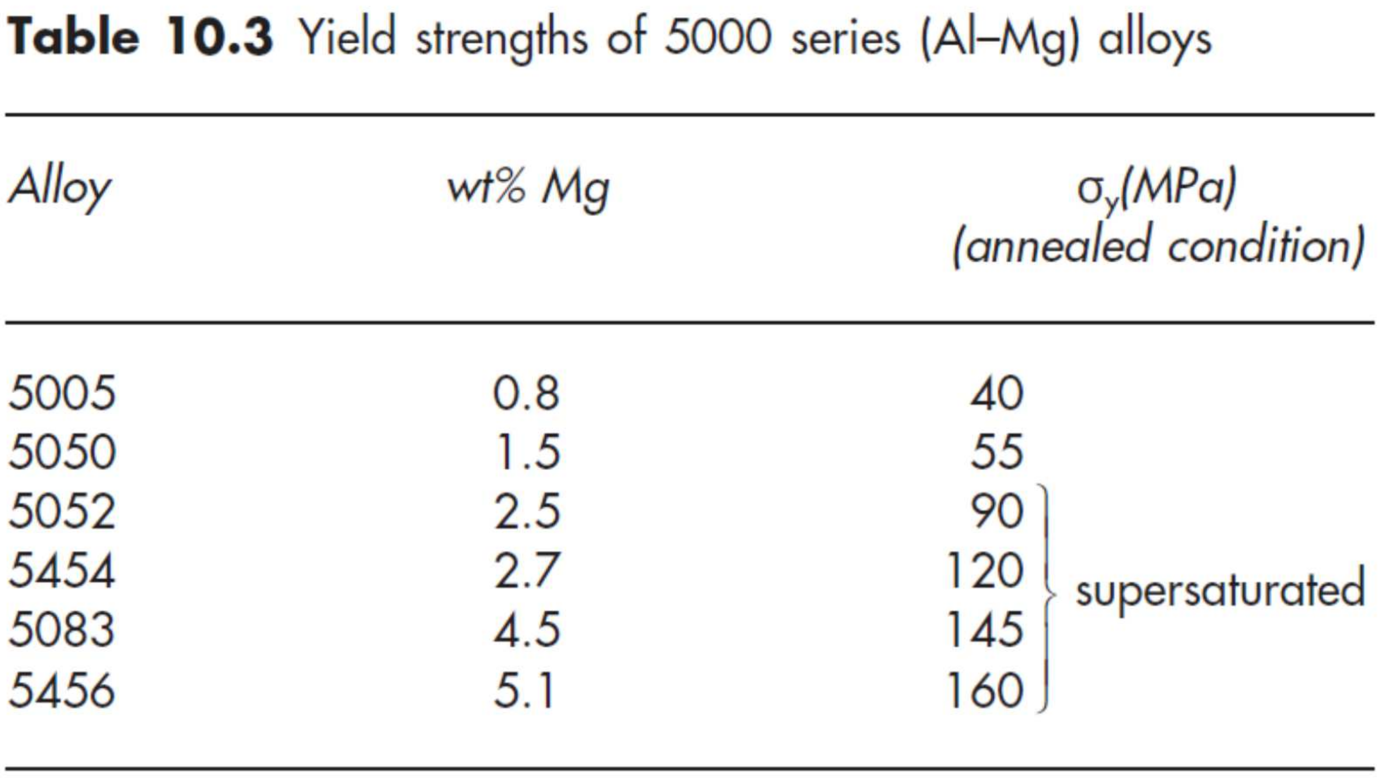


Table 10.3 Yield strengths of 5000 series (Al–Mg) alloys

Alloy	*wt% Mg*	*σ_y(MPa) (annealed condition)*	
5005	0.8	40	
5050	1.5	55	
5052	2.5	90	supersaturated
5454	2.7	120	
5083	4.5	145	
5456	5.1	160	

σ_y ↑↑

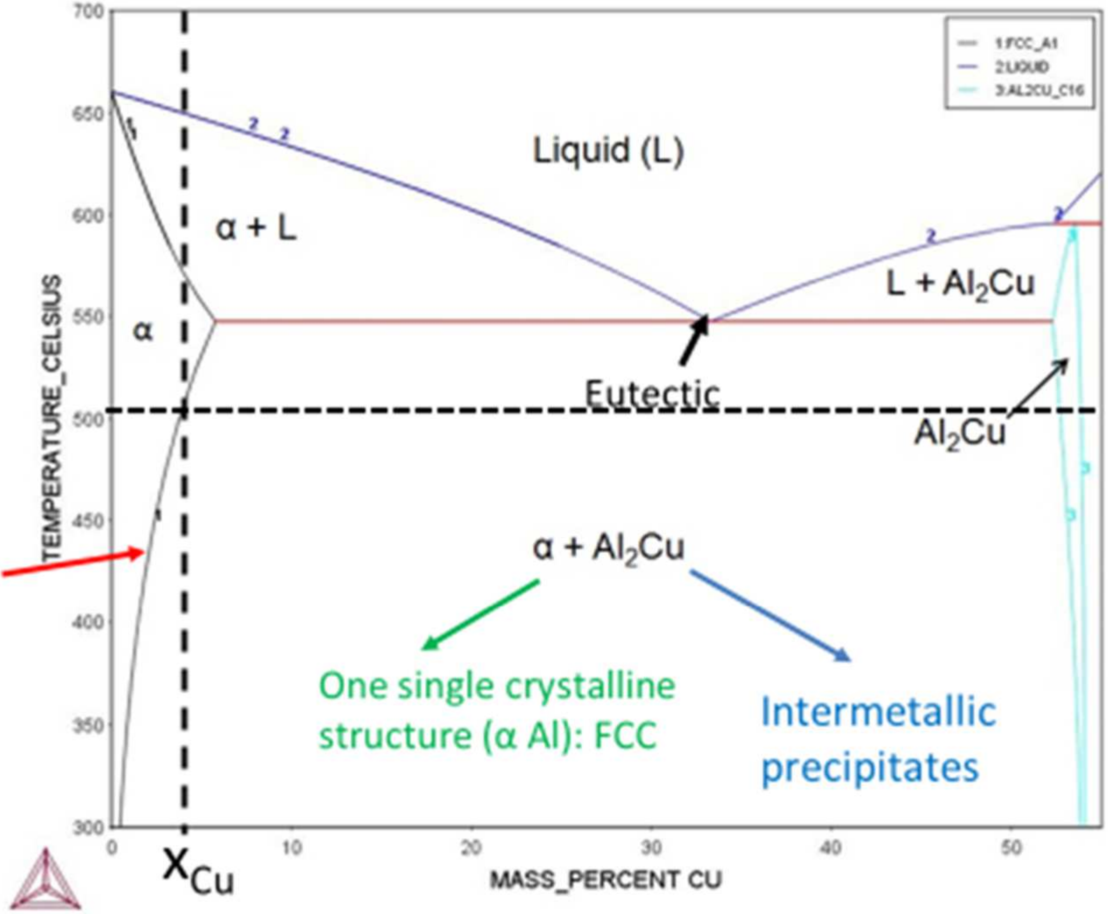
[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Solid solution strengthening (7)

- Solid solution strengthening may occur in other Al alloys (simultaneously with other strengthening mechanisms)
- In other light alloys
  - Ti-6Al-4V: strengthened by solid solution of Al and V
  - Mg alloys may be solution strengthened by Li, Al, Ag and Zn

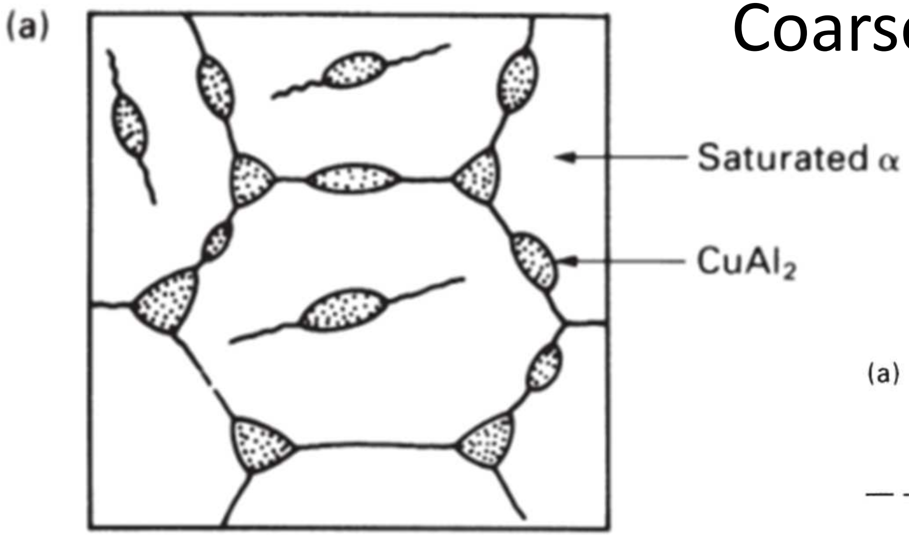
Age (precipitation) hardening (1)

- In alloys with a miscibility gap!
  E.g. Al-Cu alloys
  = 2xxx Al alloys

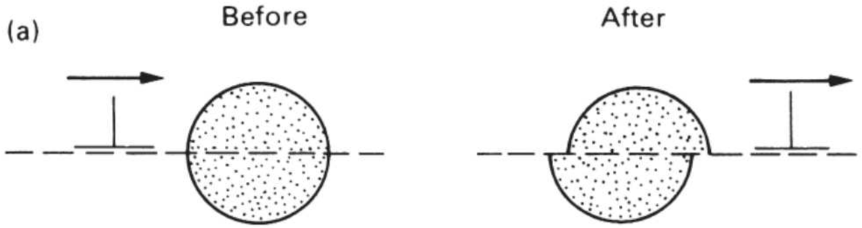


Miscibility gap - Solubility of Cu in Al decreases with T

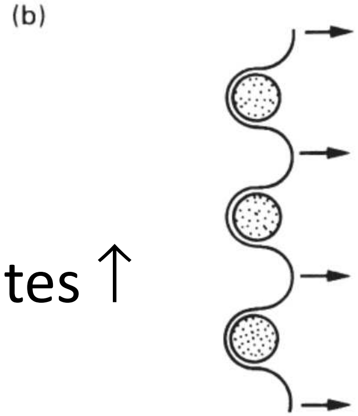
Age (precipitation) hardening (2)



Coarse widely spaced precipitates
Easily avoided by dislocations



Cutting

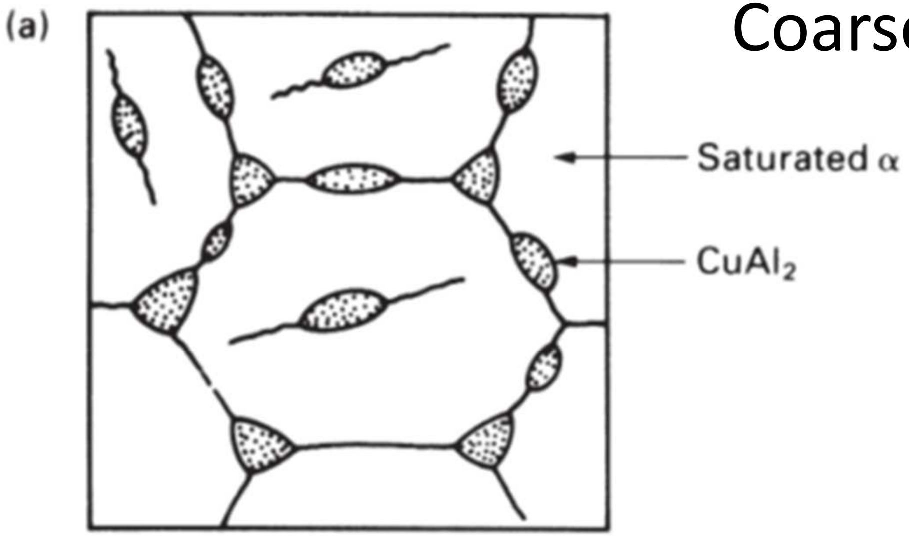


Bowing

Bowing is easier when
distance between precipitates ↑

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Age (precipitation) hardening (3)



Coarse widely spaced precipitates

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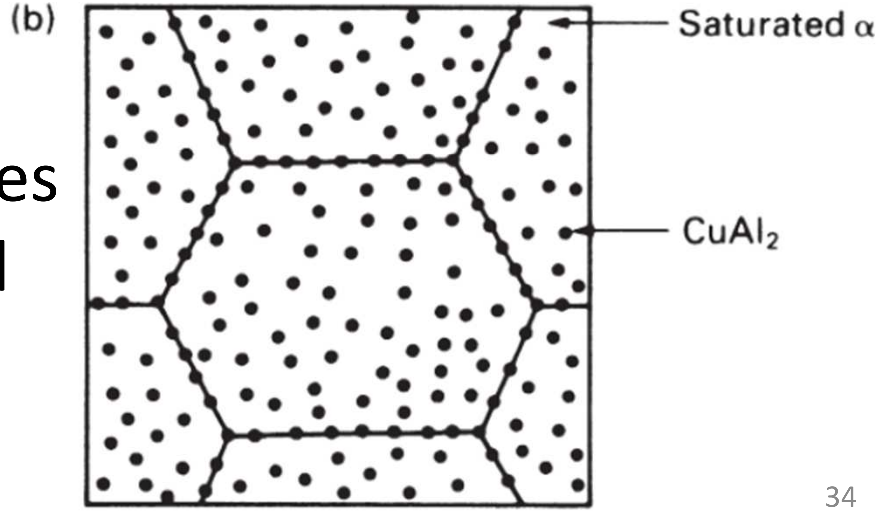
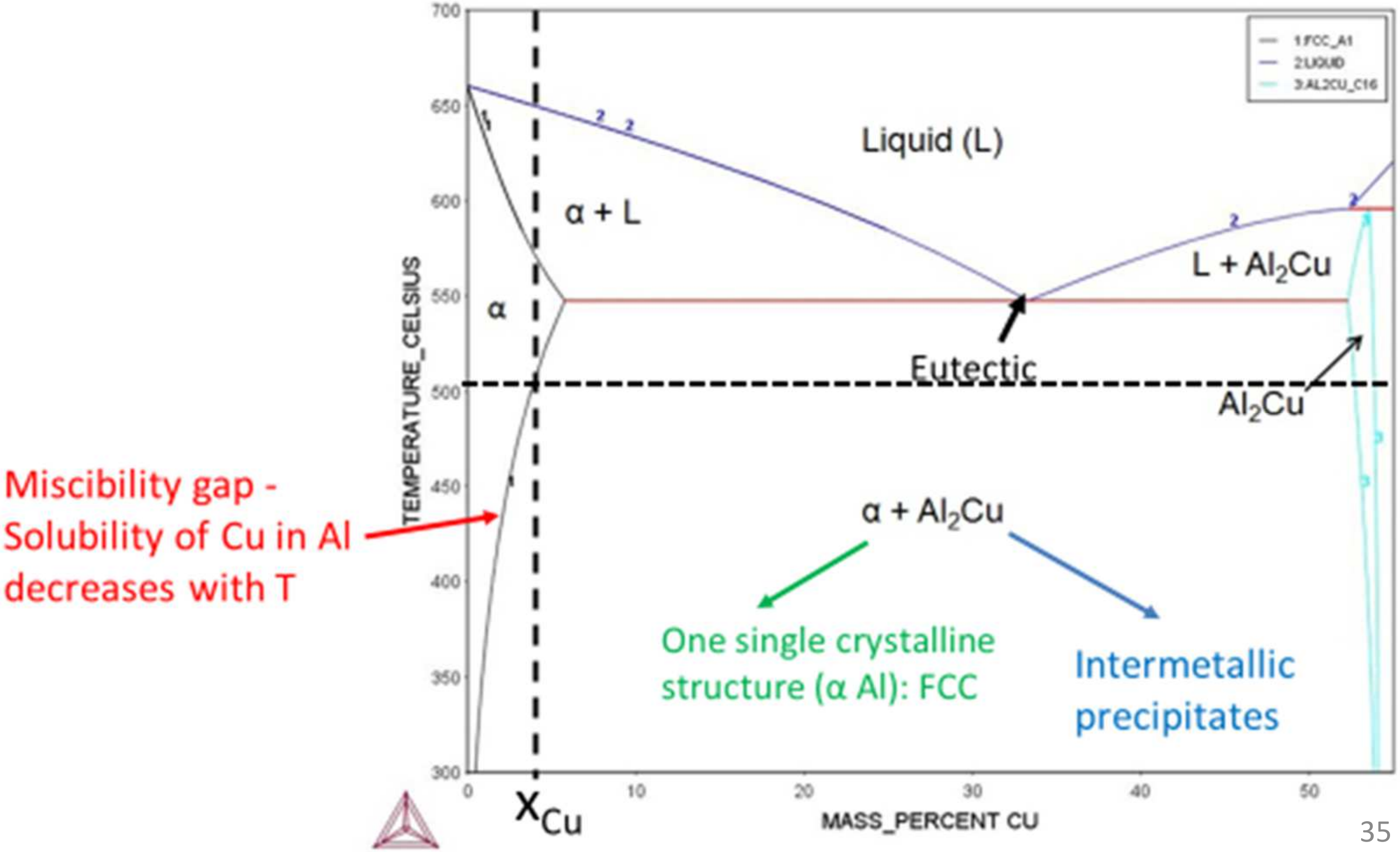


Small closely spaced precipitates
Dislocations cannot get around them!

[M.F. Ashby and D.R.H. Jones,
Engineering Materials, vol. 2]

Age (precipitation) hardening (4)

- In alloys with a miscibility gap!
  Al - 4 wt% Cu at 550°C



Miscibility gap - Solubility of Cu in Al decreases with T

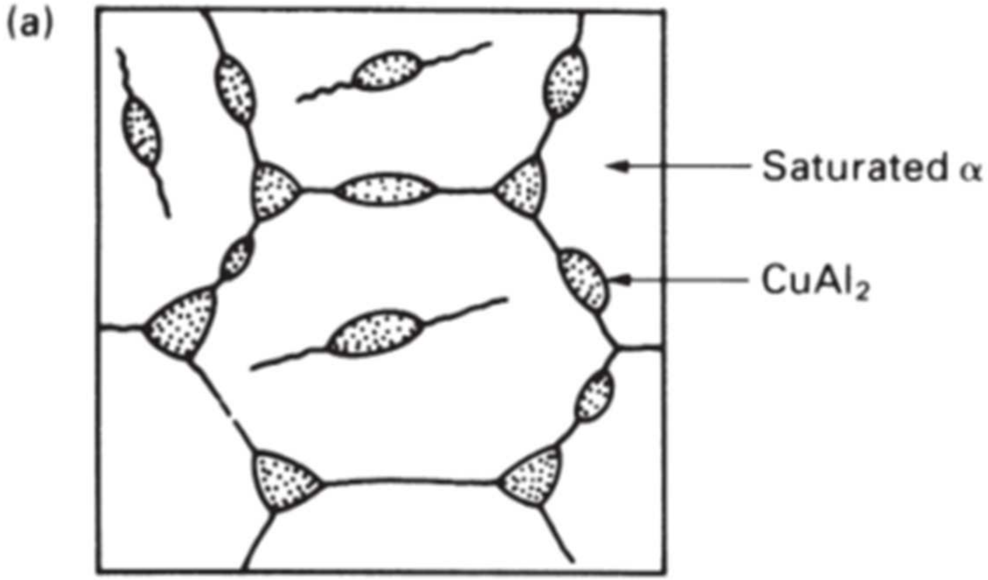
One single crystalline structure (α Al): FCC

Intermetallic precipitates

Age (precipitation) hardening (5)

- Driving force for precipitate coarsening:
  $\Delta A = -4\pi\gamma(-0{,}17 r_2^2)$
- Slow cooling from 550°C
  $\Rightarrow$ Diffusion is fast
  $\Rightarrow$ Growth rate $\uparrow$
- Nucleation rate $\downarrow$

Coarse Al_2Cu

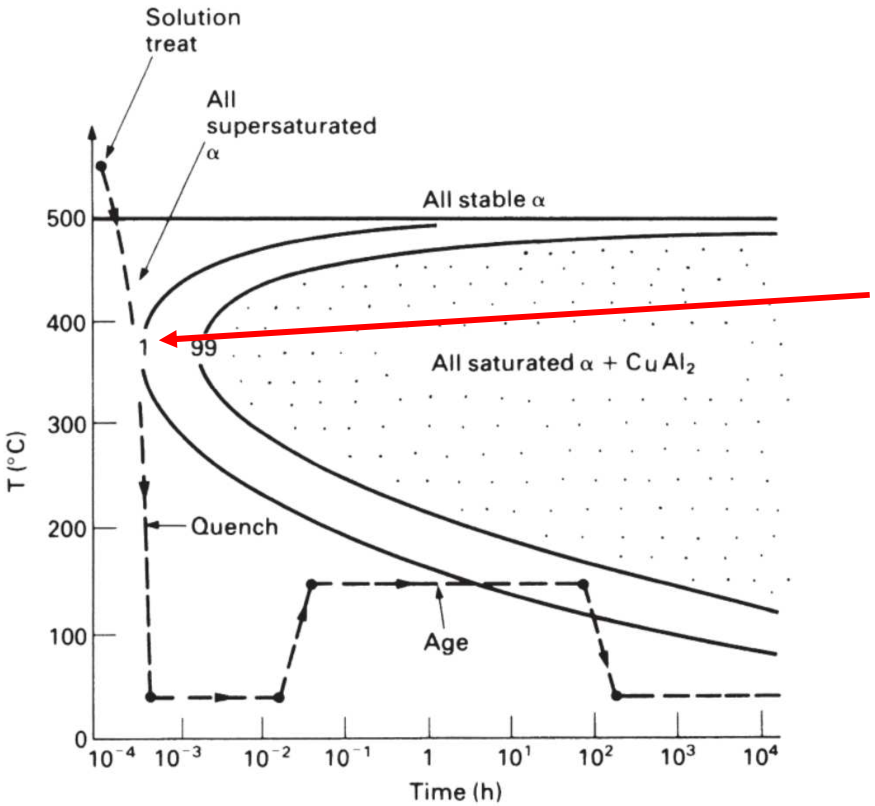


[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Age (precipitation) hardening (6)

- Rapid cooling from 550°C = **Quench**

⇒ Supersaturated solid solution of Cu in Al



Avoid diffusive phase transformations

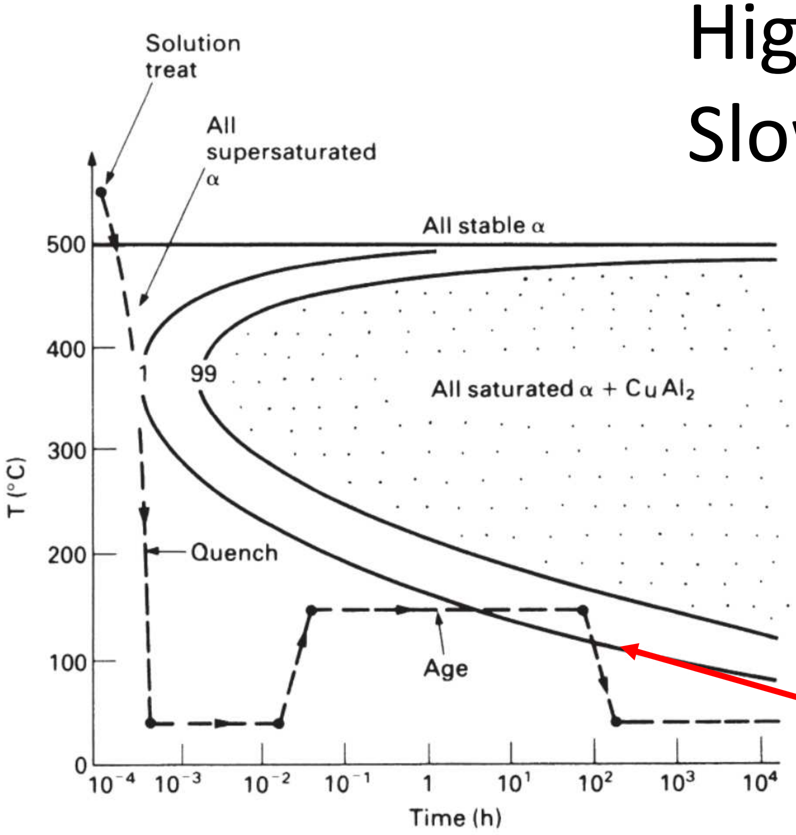
[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

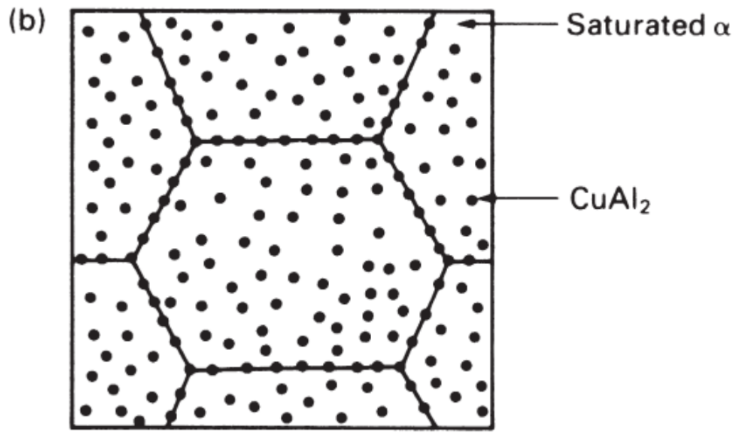
Age (precipitation) hardening (7)

- Rapid cooling from 550°C = Quench
- Isothermal hold at low T≈150°C = **Ageing**

High nucleation rate

Slow diffusion = slow growth



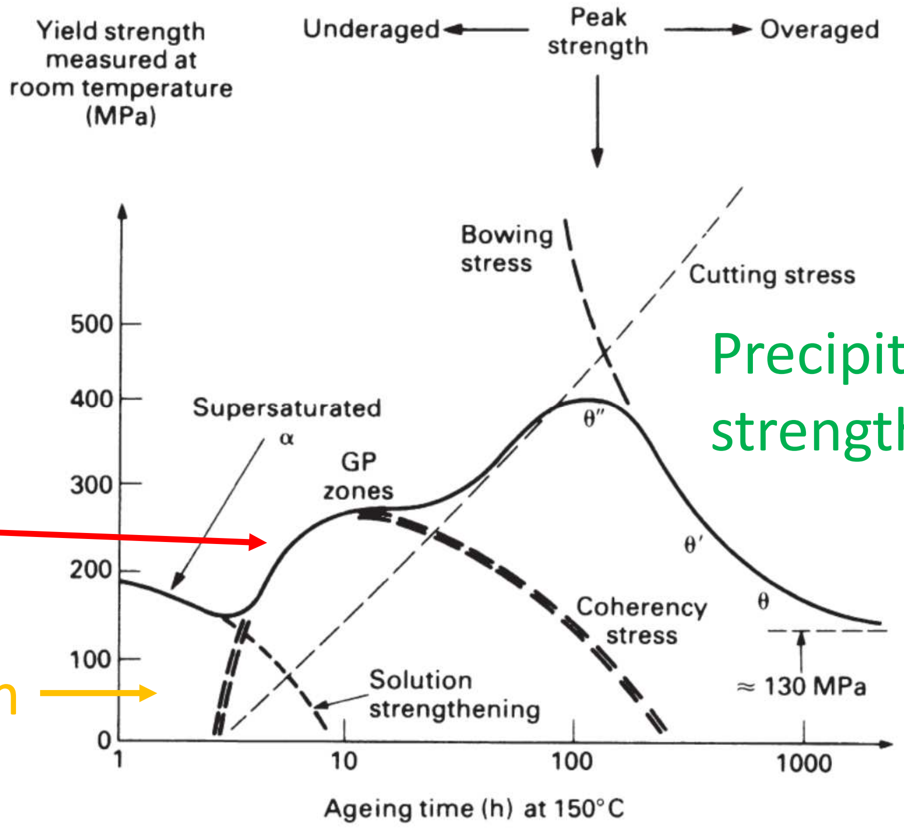


Finely dispersed precipitates

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Age (precipitation) hardening (8)

- Precipitation sequence is slow due to low atomic mobility. It is also more complex...
- At each stage: ≠ strengthening mechanisms



Precipitation strengthening

Coherency stresses (very small GP zones)

Solid solution

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Age (precipitation) hardening (9)

- Other age-hardenable alloys
  - 6xxx and 7xxx Al alloys

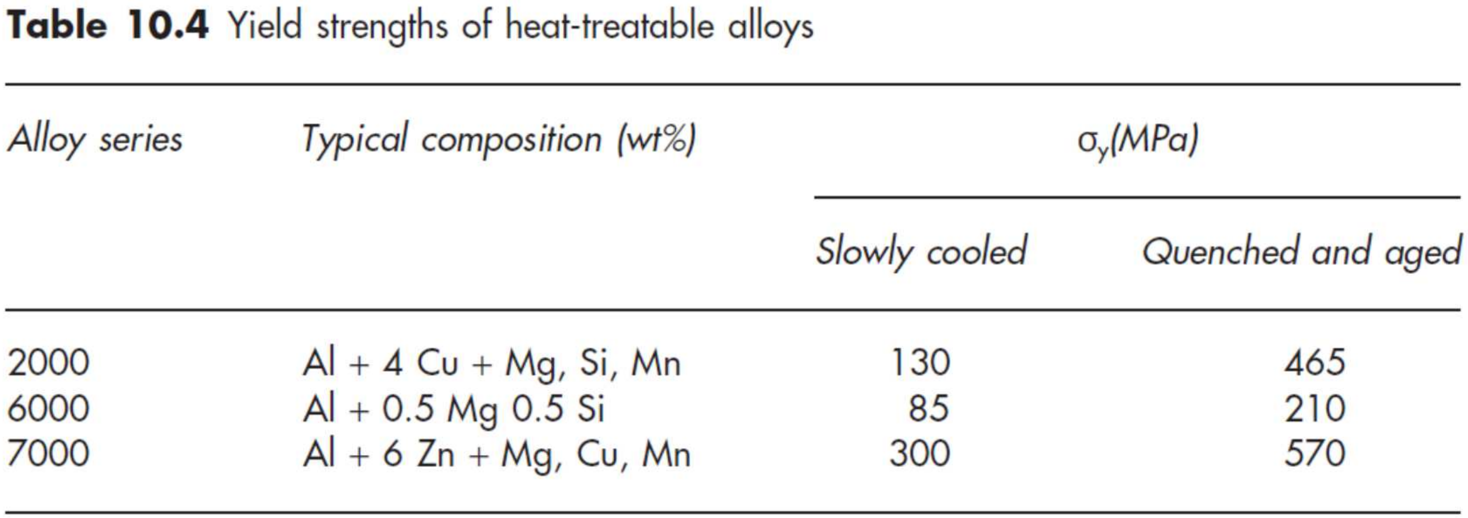


Table 10.4 Yield strengths of heat-treatable alloys

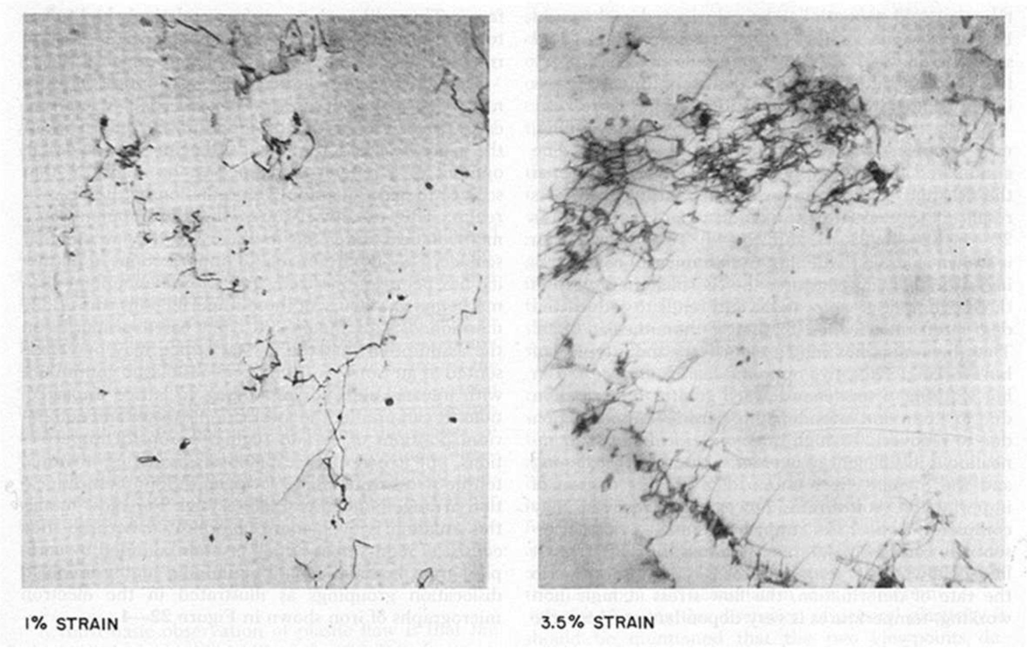
Alloy series	*Typical composition (wt%)*	σ_y*(MPa)*	
		Slowly cooled	*Quenched and aged*
2000	Al + 4 Cu + Mg, Si, Mn	130	465
6000	Al + 0.5 Mg 0.5 Si	85	210
7000	Al + 6 Zn + Mg, Cu, Mn	300	570

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

- – Mg alloys e.g.: AZ91 (9 wt% Al, 1 wt% Zn)

Work hardening (1)

- Hardening due to previous plastic strain
- $\sigma_y = A\varepsilon^n$ with A and n constants



Dislocations density$\uparrow$
$\Rightarrow$ Entanglement
$\Rightarrow$ Dislocations glide more difficult
$\Rightarrow$ Strength $\uparrow$
$\Rightarrow$ Work hardening

[J. Lecomte-Beckers, Phys0904 "Physique des Matériaux"]

Work hardening (2)

- 1xxx (CP Al), 3xxx (Al-Mn) and 5xxx (Al-Mg) Al alloys combine solid solution strengthening and work hardening

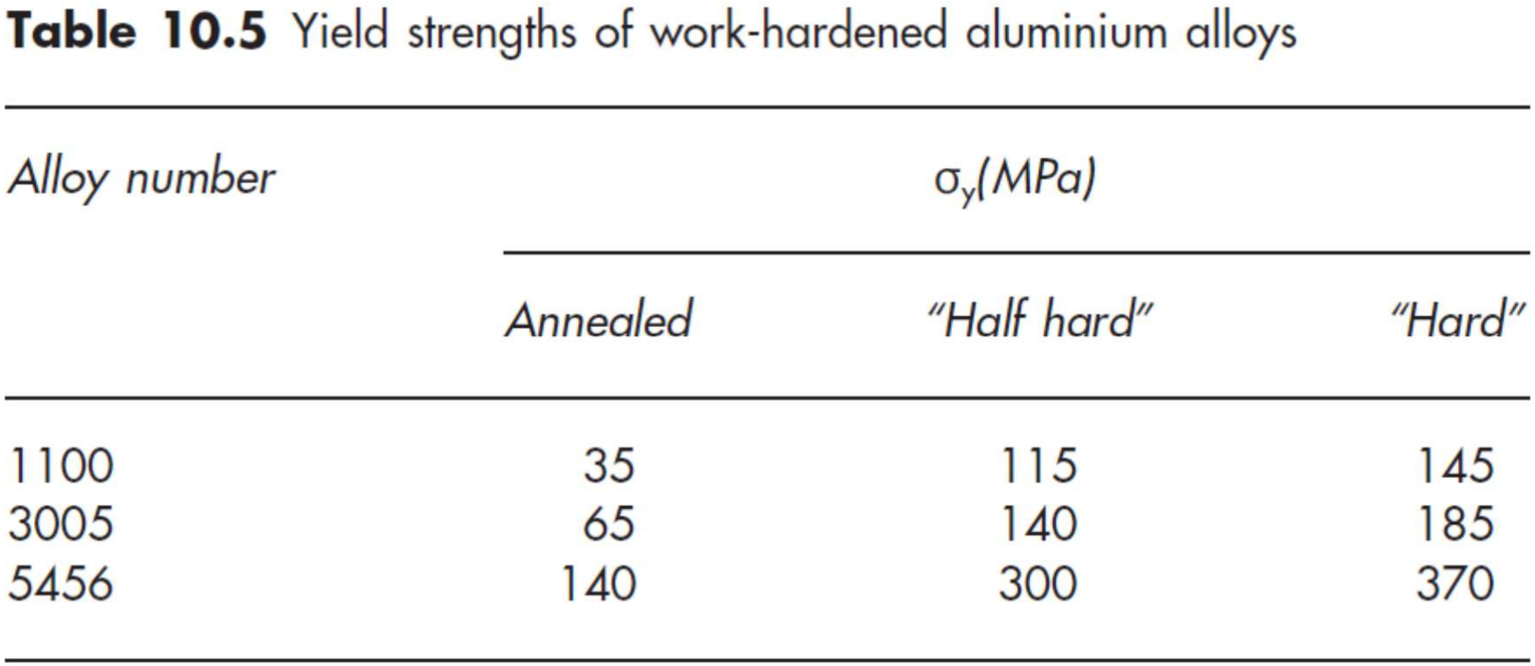


Table 10.5 Yield strengths of work-hardened aluminium alloys

Alloy number	σ_y*(MPa)*		
	Annealed	*"Half hard"*	*"Hard"*
1100	35	115	145
3005	65	140	185
5456	140	300	370

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Light alloys

- Standard designations for **wrought Al alloys**: International Alloy Designation System for wrought products (IADS)
- Four digits number
  - 1st digit: major alloying element
    1xxx commercial purity Al
    2xxx Al-Cu alloys
    6xxx Al-Mg-Si alloys
  - 3rd and 4th digits identify the specific alloy composition (or purity level in 1xxx series)
  - 2d digit indicates purity level or alloy modification
- AA5xxx are Al-Mg alloys
  AA5082 and AA5083 are two different alloys
  AA5182 and 5282 are two variants of the same alloys (with very little differences in composition)

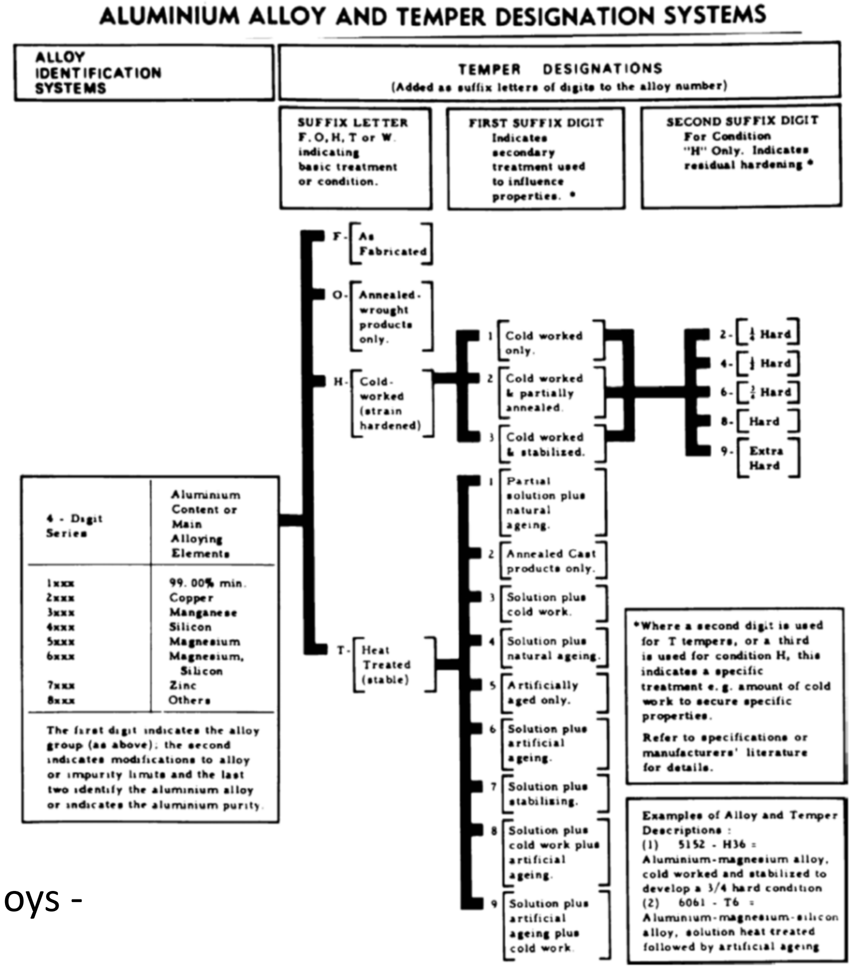
Light alloys

- Standard designations for **wrought** Al alloys: International Alloy Designation System for wrought products (IADS)

- Designation of **temper** (thermal or other treatments)
  - F : as-fabricated
  - O : annealed condition
  - H : strain hardened
  - T + digits : thermal treatment
    T4 : solution treatment
    T5 : rapid cooling after high T processing
    T6 : solution treatment + quenching + artificial ageing

Light alloys

- Standard designations for **wrought** Al alloys: International Alloy Designation System for wrought products (IADS)



ALUMINIUM ALLOY AND TEMPER DESIGNATION SYSTEMS

ALLOY IDENTIFICATION SYSTEMS

TEMPER DESIGNATIONS
(Added as suffix letters of digits to the alloy number)

SUFFIX LETTER F, O, H, T or W. indicating basic treatment or condition.

FIRST SUFFIX DIGIT Indicates secondary treatment used to influence properties. *

SECOND SUFFIX DIGIT For Condition "H" Only. Indicates residual hardening *

4 - Digit Series	Aluminium Content or Main Alloying Elements
1xxx	99.00% min.
2xxx	Copper
3xxx	Manganese
4xxx	Silicon
5xxx	Magnesium
6xxx	Magnesium, Silicon
7xxx	Zinc
8xxx	Others

The first digit indicates the alloy group (as above); the second indicates modifications to alloy or impurity limits and the last two identify the aluminium alloy or indicates the aluminium purity.

*Where a second digit is used for T tempers, or a third is used for condition H, this indicates a specific treatment e.g. amount of cold work to secure specific properties.

Refer to specifications or manufacturers' literature for details.

Examples of Alloy and Temper Descriptions :
(1) 5152 - H36 = Aluminium-magnesium alloy, cold worked and stabilized to develop a 3/4 hard condition
(2) 6061 - T6 = Aluminium-magnesium-silicon alloy, solution heat treated followed by artificial ageing

[I.J. Polmear et al., Light alloys - Metallurgy of light metals]

Light alloys

- Standard designations for cast Al alloys
  US Aluminium Association System

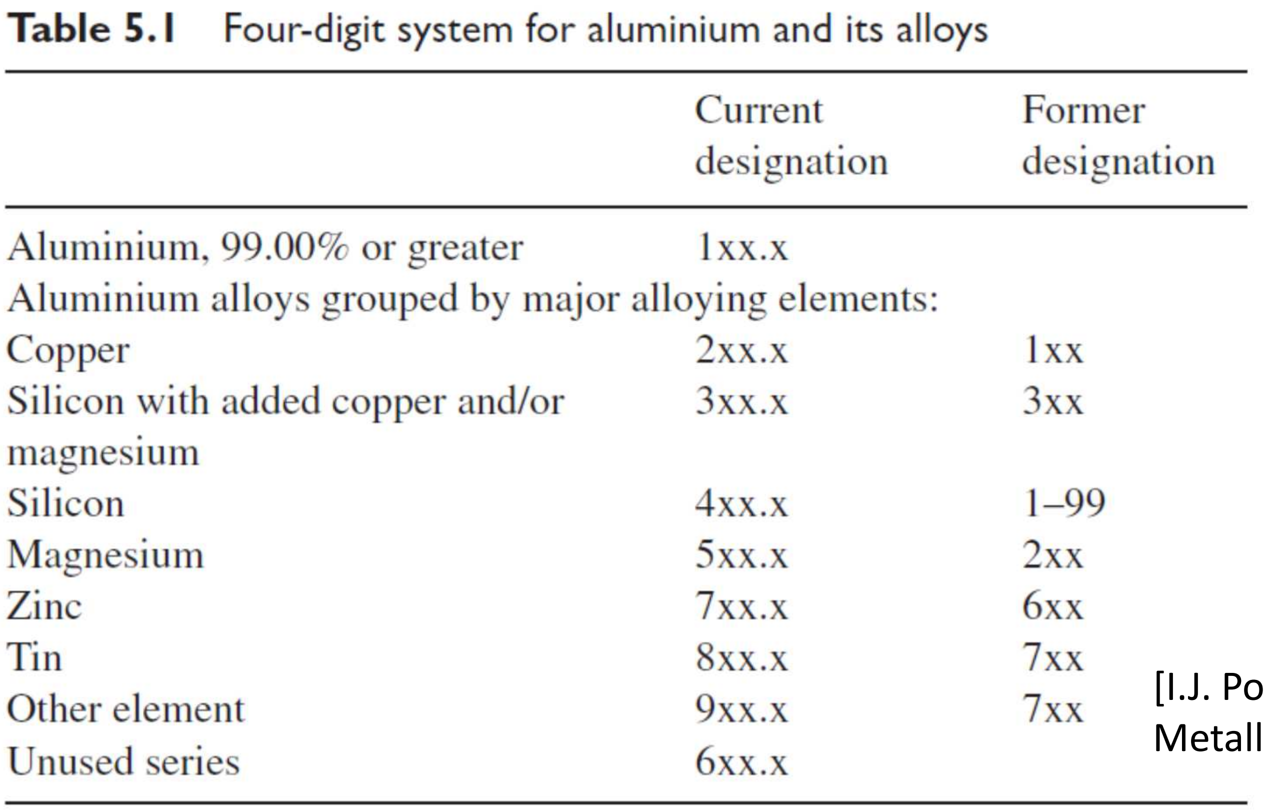


Table 5.1 Four-digit system for aluminium and its alloys

	Current designation	Former designation
Aluminium, 99.00% or greater	1xx.x	
Aluminium alloys grouped by major alloying elements:		
Copper	2xx.x	1xx
Silicon with added copper and/or magnesium	3xx.x	3xx
Silicon	4xx.x	1–99
Magnesium	5xx.x	2xx
Zinc	7xx.x	6xx
Tin	8xx.x	7xx
Other element	9xx.x	7xx
Unused series	6xx.x	

[I.J. Polmear et al., Light alloys - Metallurgy of light metals]

Other system: British: LM + number + suffix for casting condition

Light alloys

- Standard designations for Mg alloys : ASTM
  Letters for main alloying elements
  A : aluminium
  E : rare earths (Sc, Y, Ce...)
  M : manganese
  S : silicium
  Z : zinc

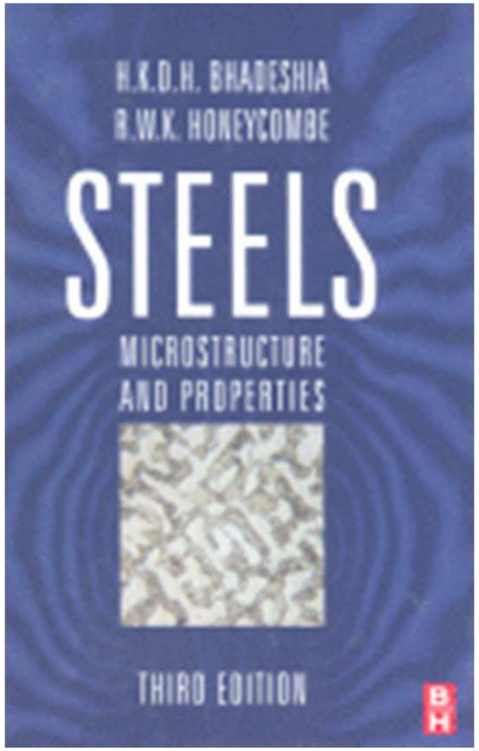
  Examples:
  AZ91 : Mg + 9% Al + 1% Zn
  AM50 : Mg + 5% Al + 0,3 % Mn
  AS41 : Mg + 4% Al + 1% Si
  ...

Outline

- Introduction
- Light alloys
- Carbon steels
  - Carbon as main alloying element
- Alloy steels
- Production, forming and joining of metals

Steels

- A good reference:
  "Steels - microstructure and properties" by
  H.K.D.H. Bhadeshia and R.W.K. Honeycombe, (2006)
  Available from ULiege library



Carbon steels

Carbon as main alloying element

Carbon steels

- Large range of properties and usage depending on Carbon content and heat treatment

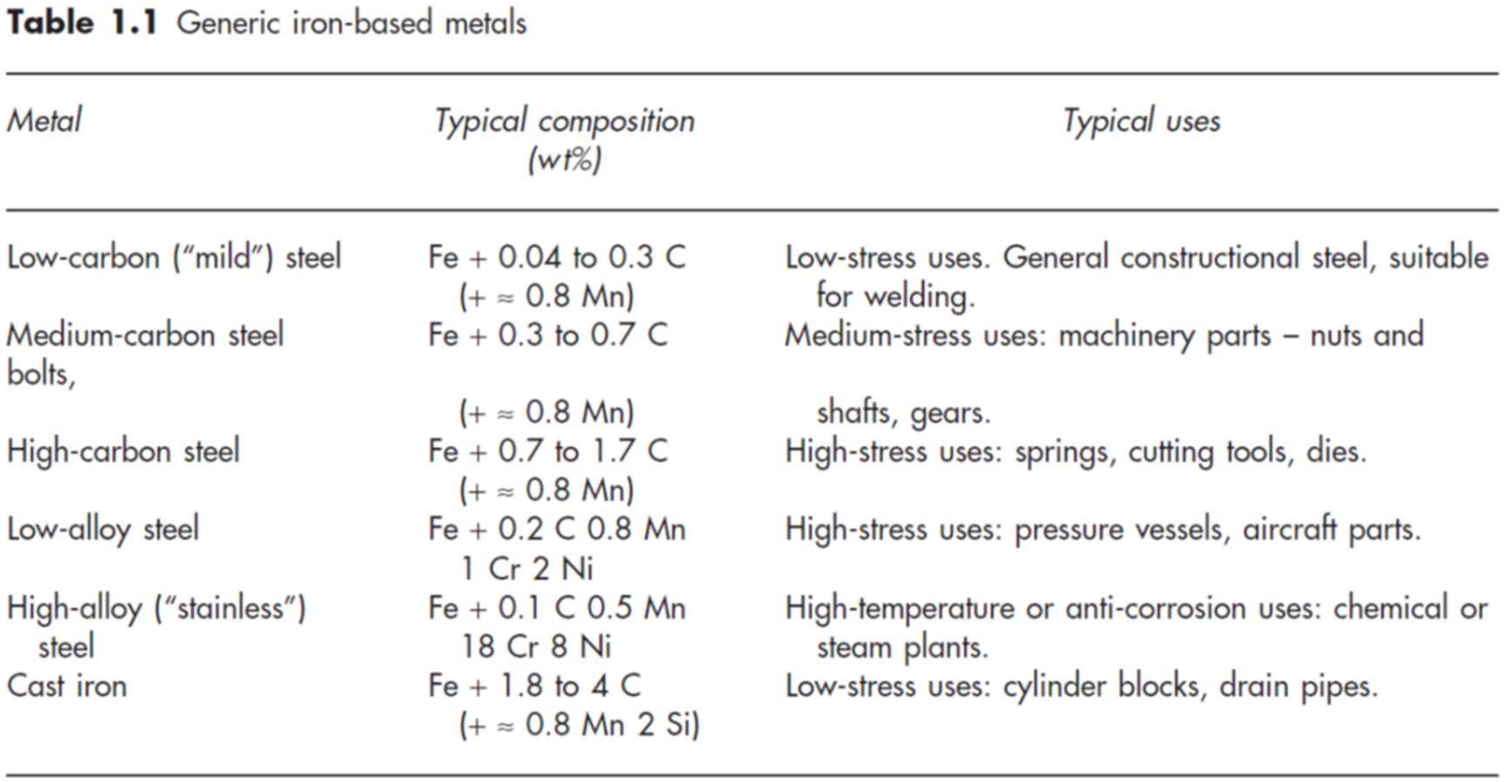


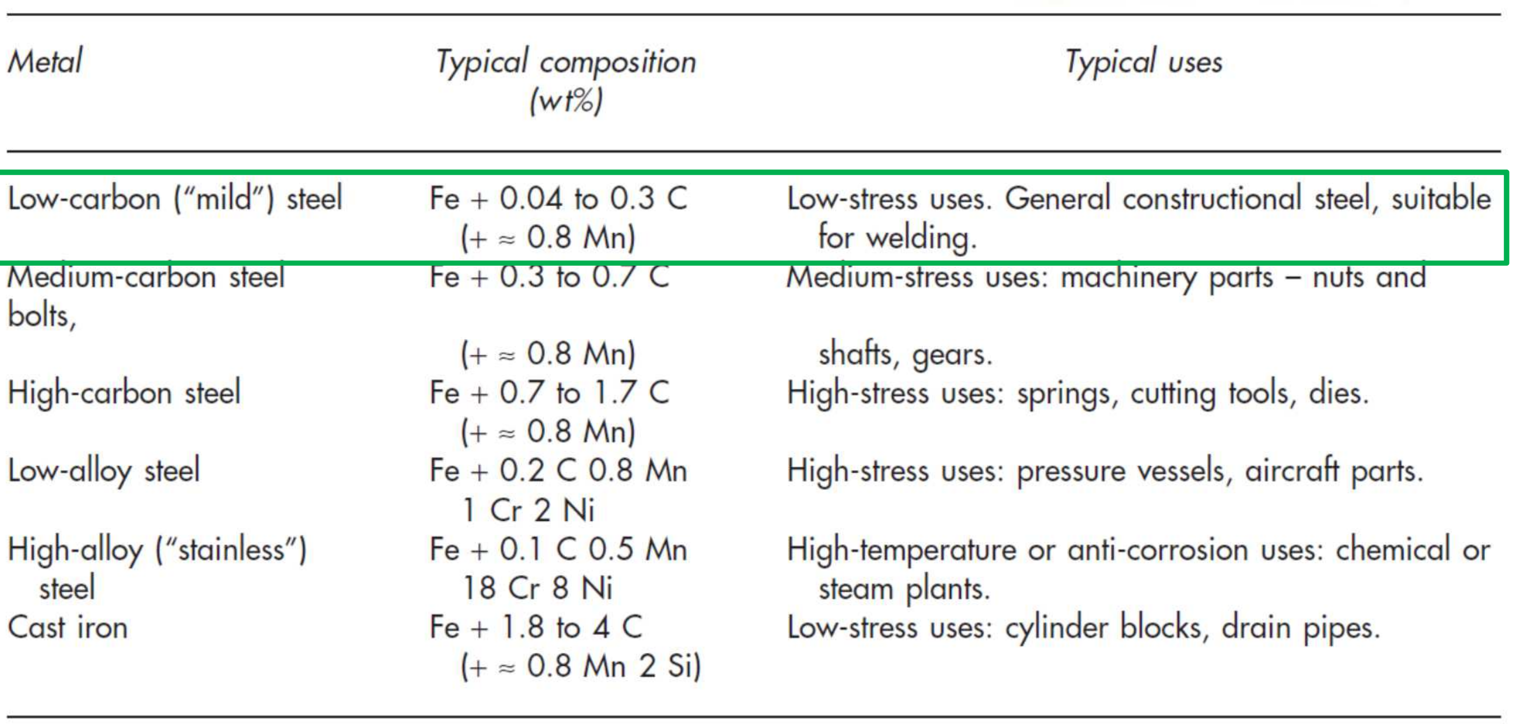
Table 1.1 Generic iron-based metals

Metal	*Typical composition (wt%)*	*Typical uses*
Low-carbon ("mild") steel	Fe + 0.04 to 0.3 C (+ ≈ 0.8 Mn)	Low-stress uses. General constructional steel, suitable for welding.
Medium-carbon steel bolts,	Fe + 0.3 to 0.7 C (+ ≈ 0.8 Mn)	Medium-stress uses: machinery parts – nuts and shafts, gears.
High-carbon steel	Fe + 0.7 to 1.7 C (+ ≈ 0.8 Mn)	High-stress uses: springs, cutting tools, dies.
Low-alloy steel	Fe + 0.2 C 0.8 Mn 1 Cr 2 Ni	High-stress uses: pressure vessels, aircraft parts.
High-alloy ("stainless") steel	Fe + 0.1 C 0.5 Mn 18 Cr 8 Ni	High-temperature or anti-corrosion uses: chemical or steam plants.
Cast iron	Fe + 1.8 to 4 C (+ ≈ 0.8 Mn 2 Si)	Low-stress uses: cylinder blocks, drain pipes.

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Use of carbon steels (1)

Table 1.1 Generic iron-based metals



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Cast iron	Fe + 1.8 to 4 C (+ ≈ 0.8 Mn 2 Si)	Low-stress uses: cylinder blocks, drain pipes.

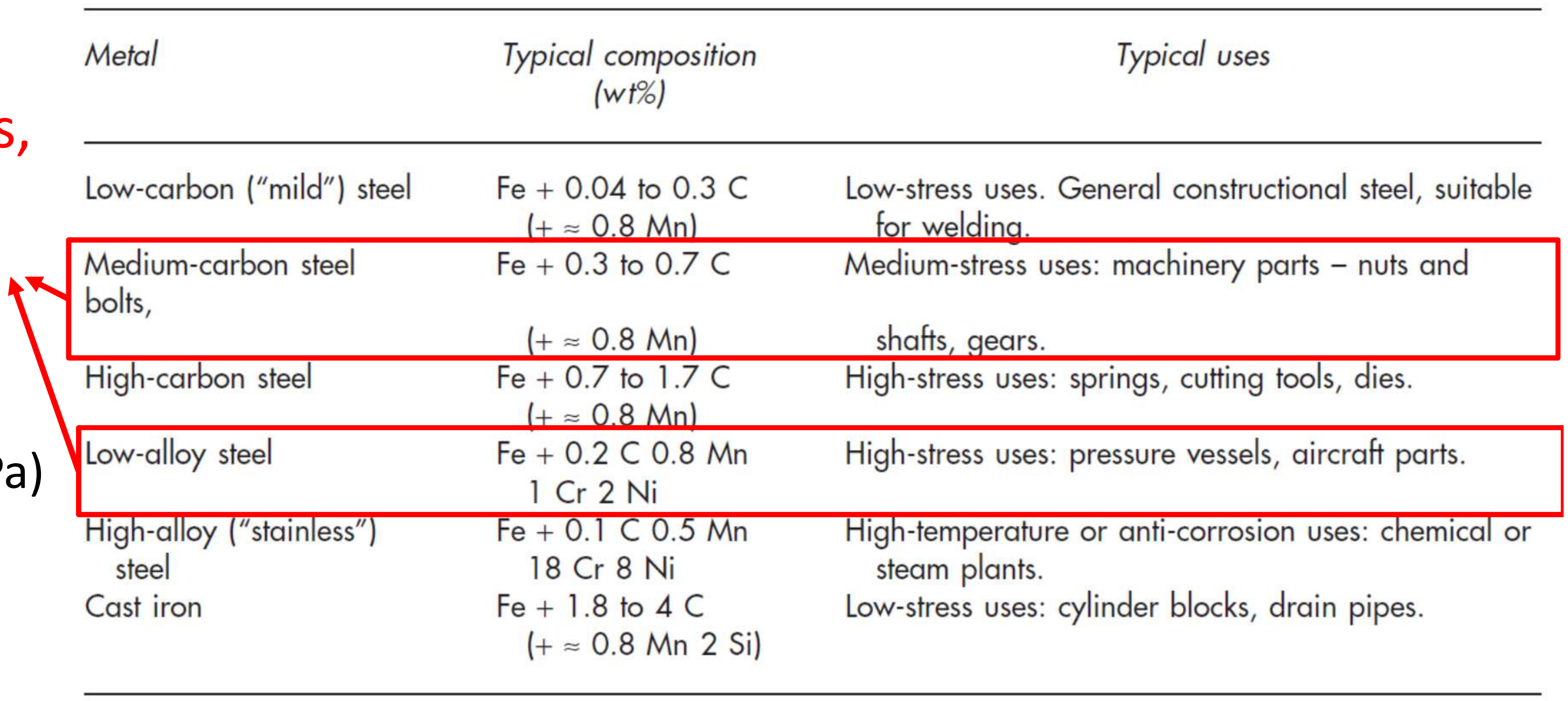
Wheels, frame

- low loads (σ_y~220 MPa)
- easy to cut, bend...
- cheap

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Use of carbon steels (2)

Table 1.1 Generic iron-based metals



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Cast iron	Fe + 1.8 to 4 C (+ ≈ 0.8 Mn 2 Si)	Low-stress uses: cylinder blocks, drain pipes.

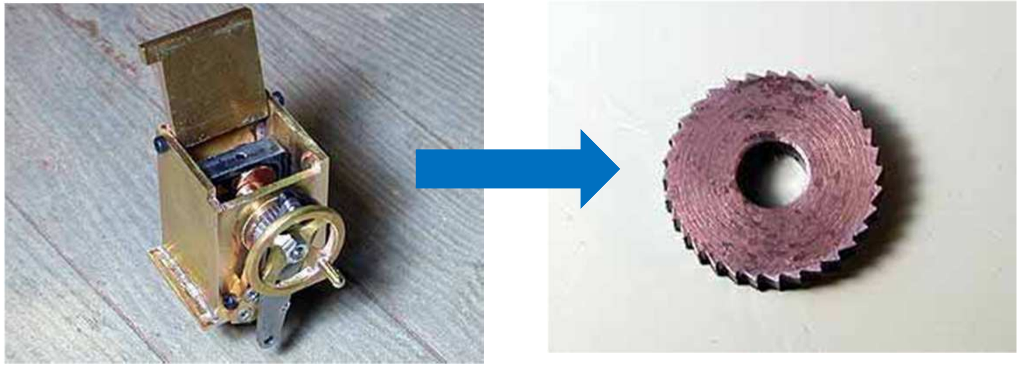
Drive shafts, gear-wheel teeths

- higher stresses (σ_y~400 MPa)

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Use of carbon steels (3)

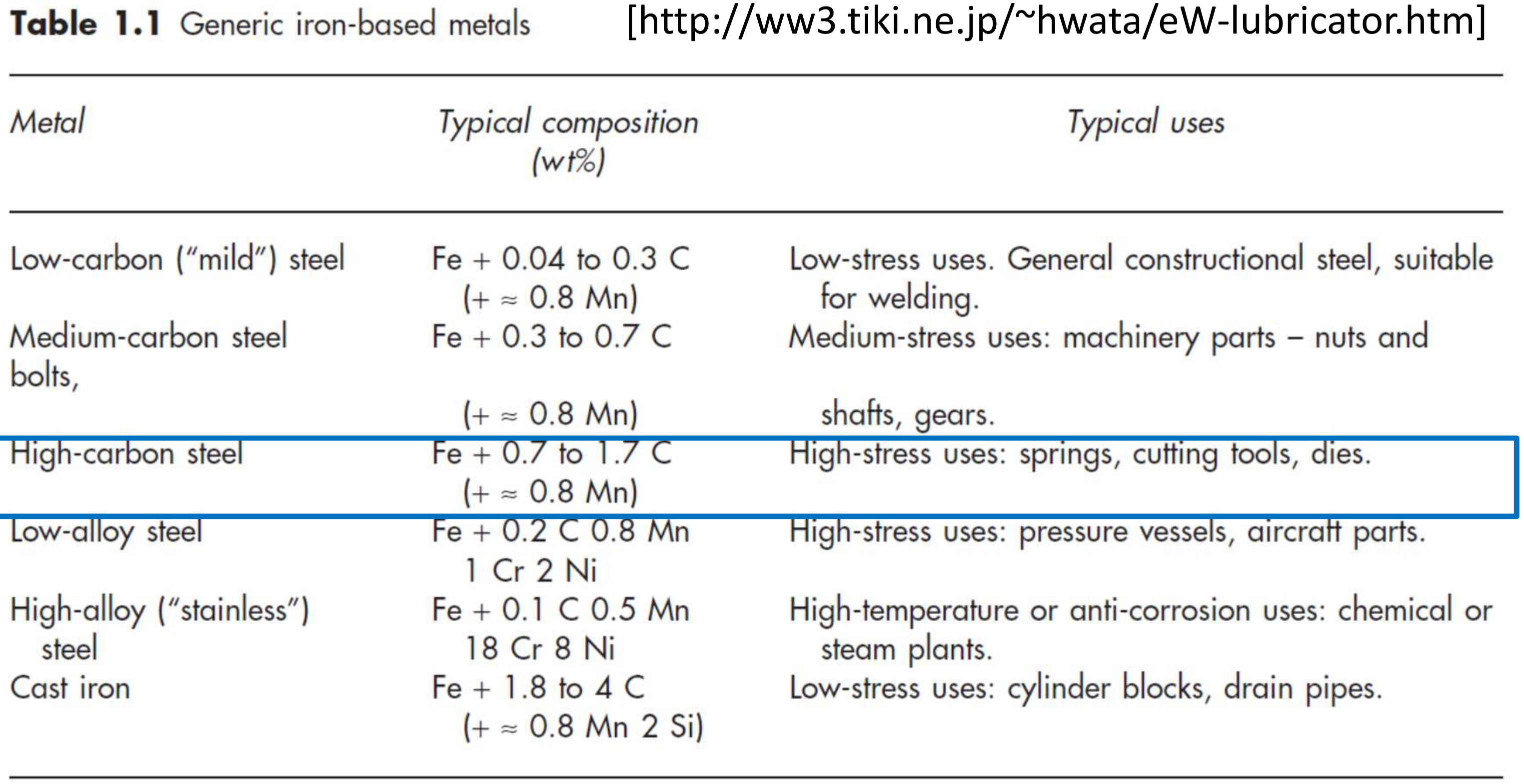
+ Heat treatment



[http://ww3.tiki.ne.jp/~hwata/eW-lubricator.htm]

Mechanical lubricator

- High friction and wear
- Quenched and tempered high carbon steels (σ_y~1000MPa)



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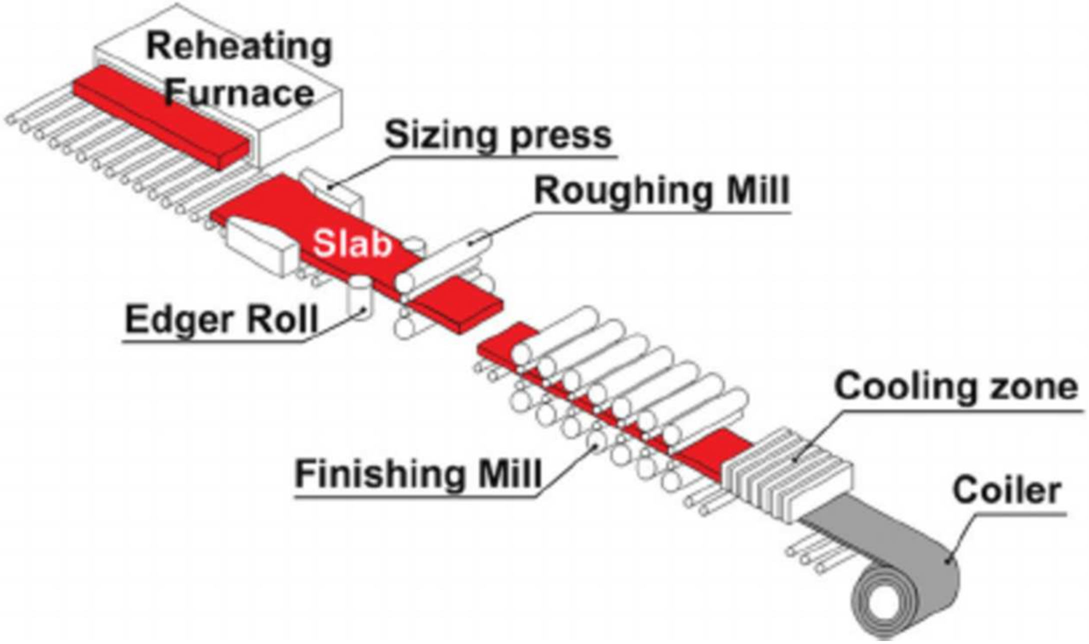
[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Normalised carbon steels

- "Off the shelf" steels
  - Microstructures produced by hot rolling + slow cooling
  - Close to equilibrium microstructures

⇒ **Phase diagram**



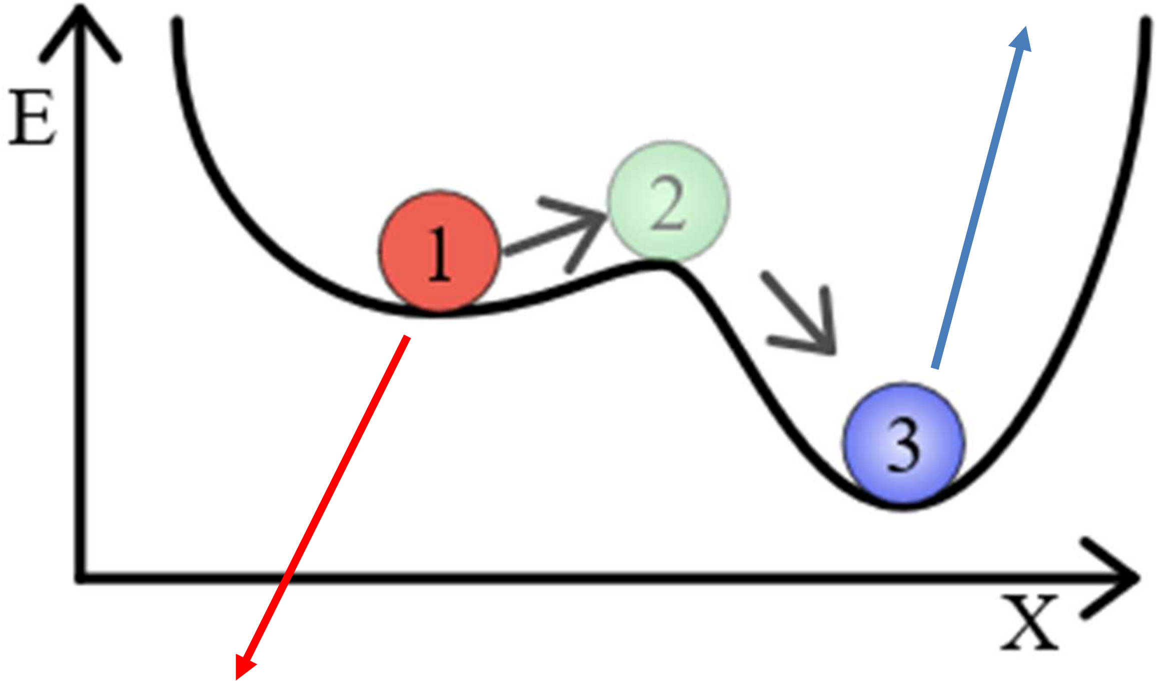
[Lee et al., Adv. Mech. Eng., 2015]

Fe + C

Equilibrium = G minimum !

Absolute minimum

Fe - C graphite: stable

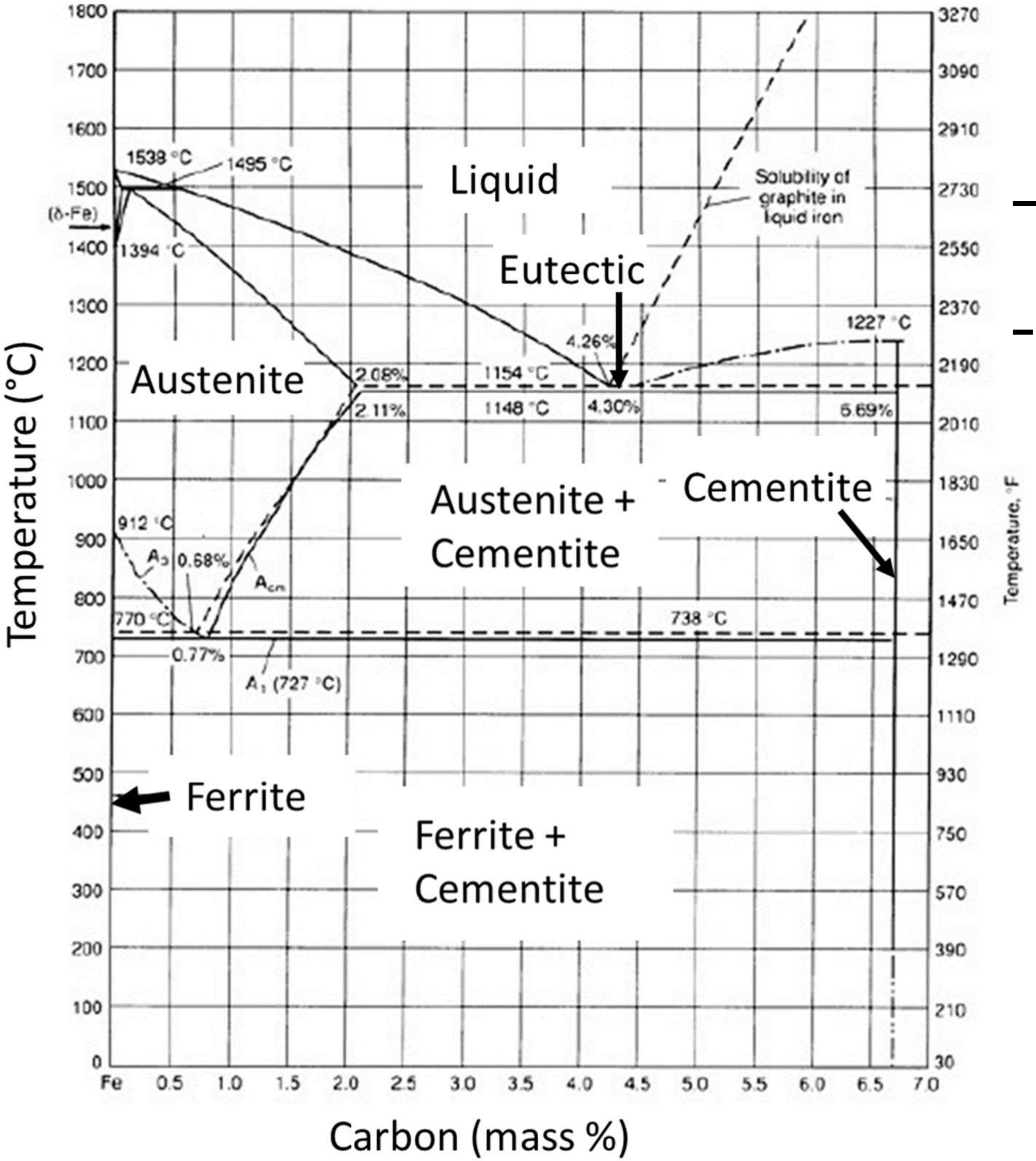


Relative minimum

Fe - Fe_3C (cementite): metastable

[Wikimedia]

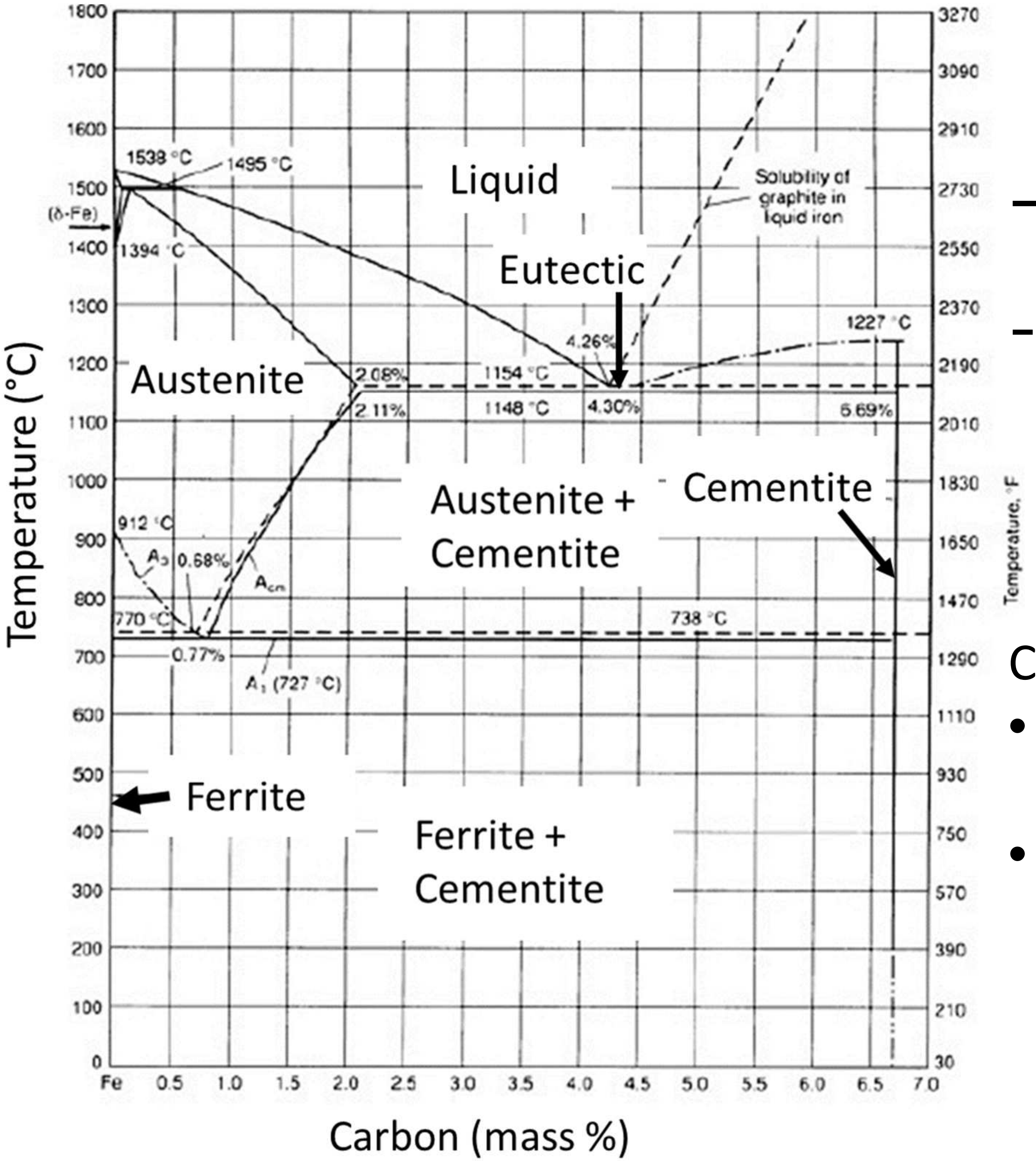
Fe + C



—— Metastable, Fe-Fe_3C

- - - Stable, Fe-C graphite

Fe + C



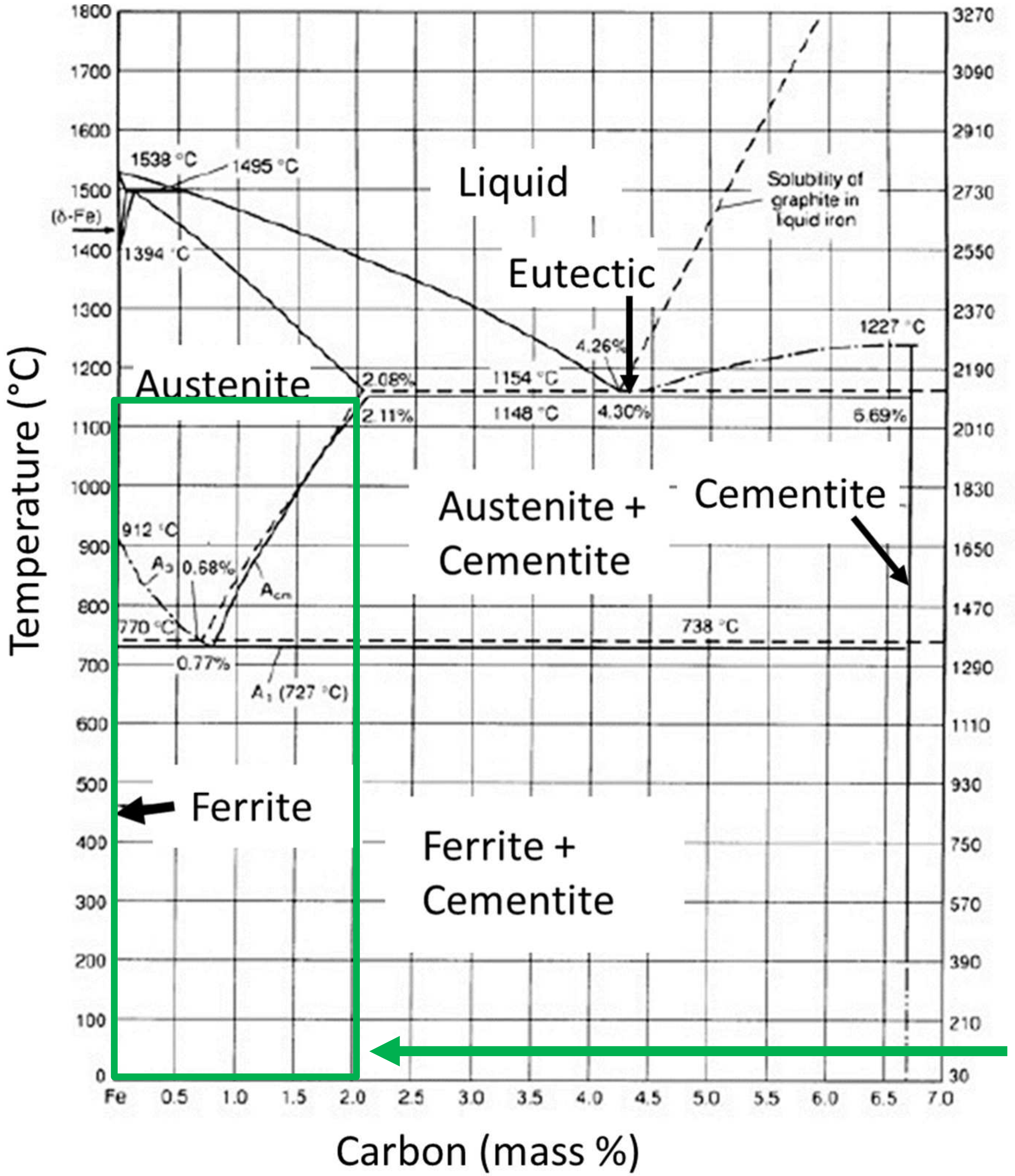
—— Metastable, Fe-Fe_3C

- - - Stable, Fe-C graphite

C content

- < 2 mass % C: **steel Fe-Fe_3C diagram**
- > 2 mass % C: **cast iron**

Fe + C



—— Metastable, Fe-Fe_3C

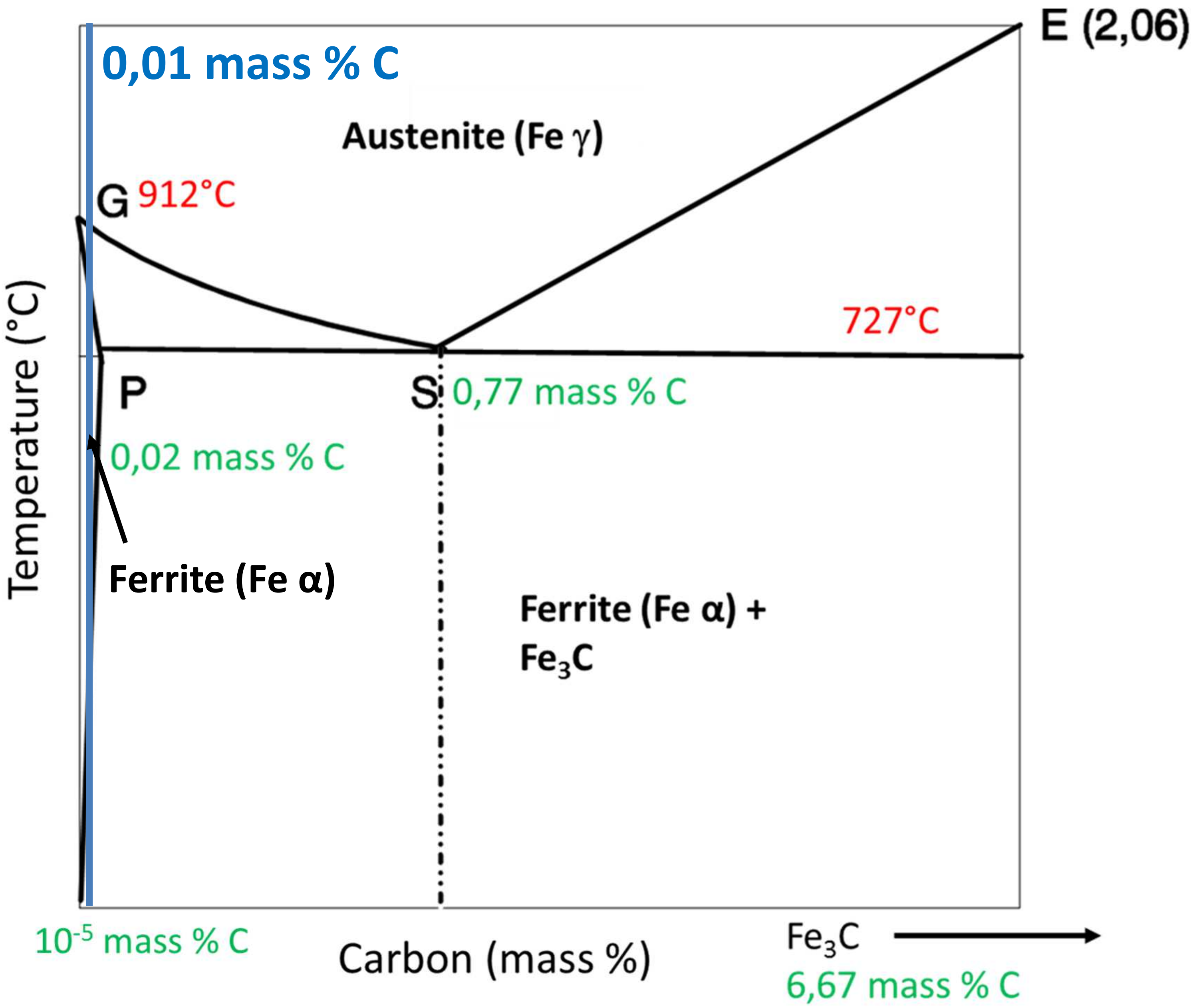
- - - Stable, Fe-C graphite

C content

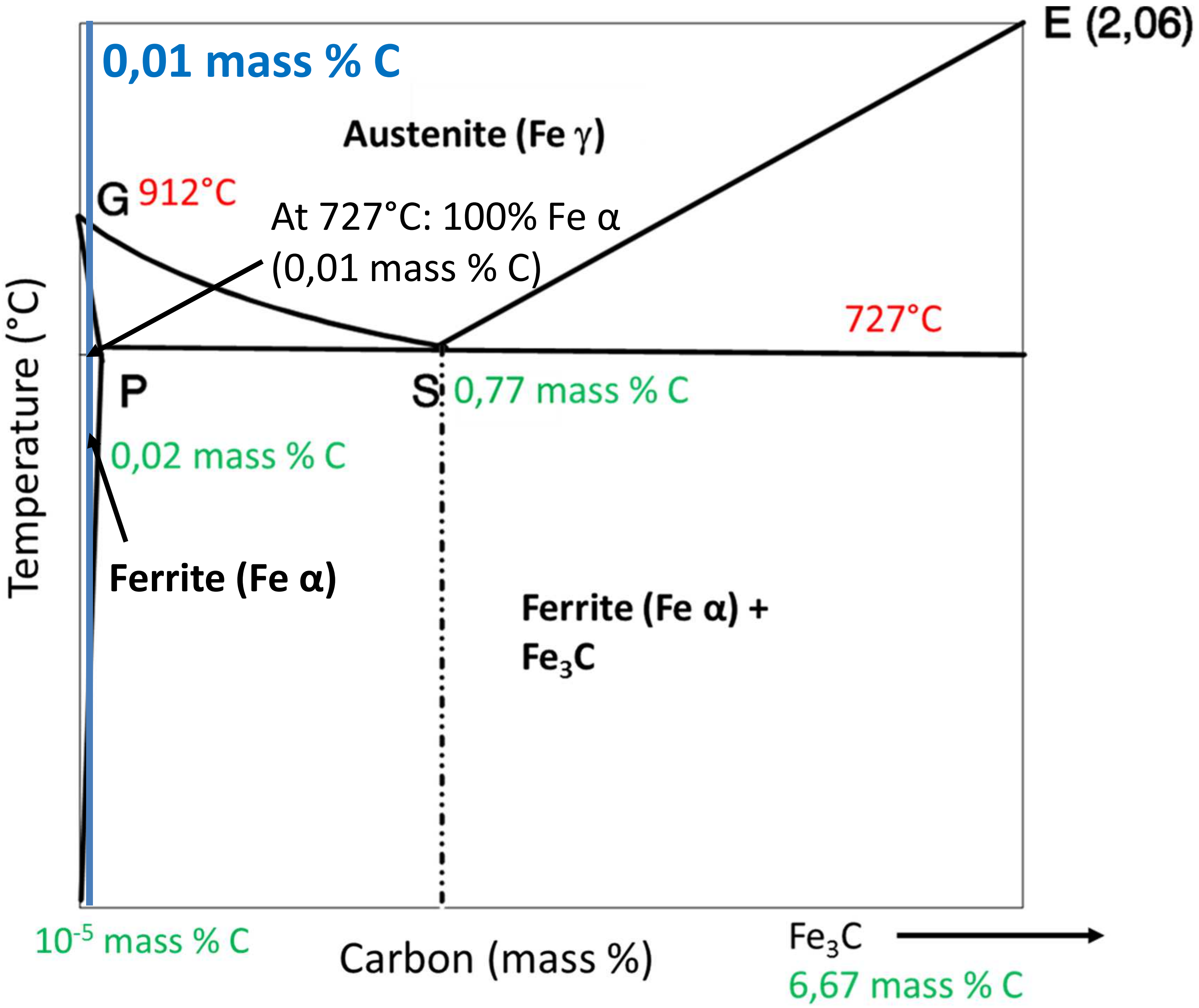
- < 2 mass % C: **steel**
  Fe-Fe_3C diagram
- > 2 mass % C: **cast iron**

Zone of interest for steel

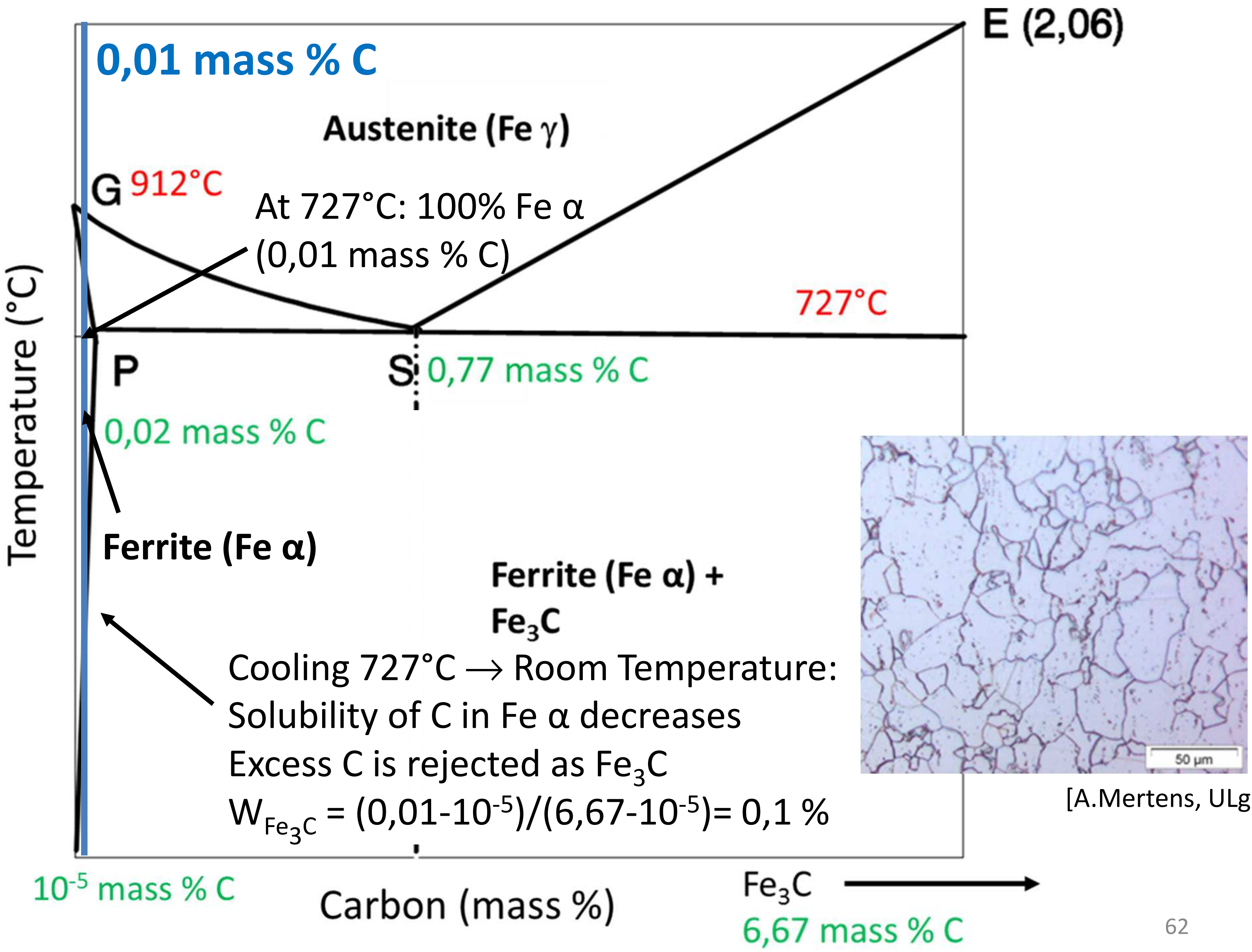
Ferritic steel (< 0,02 mass % C)



Ferritic steel (< 0,02 mass % C)



Ferritic steel (< 0,02 mass % C)

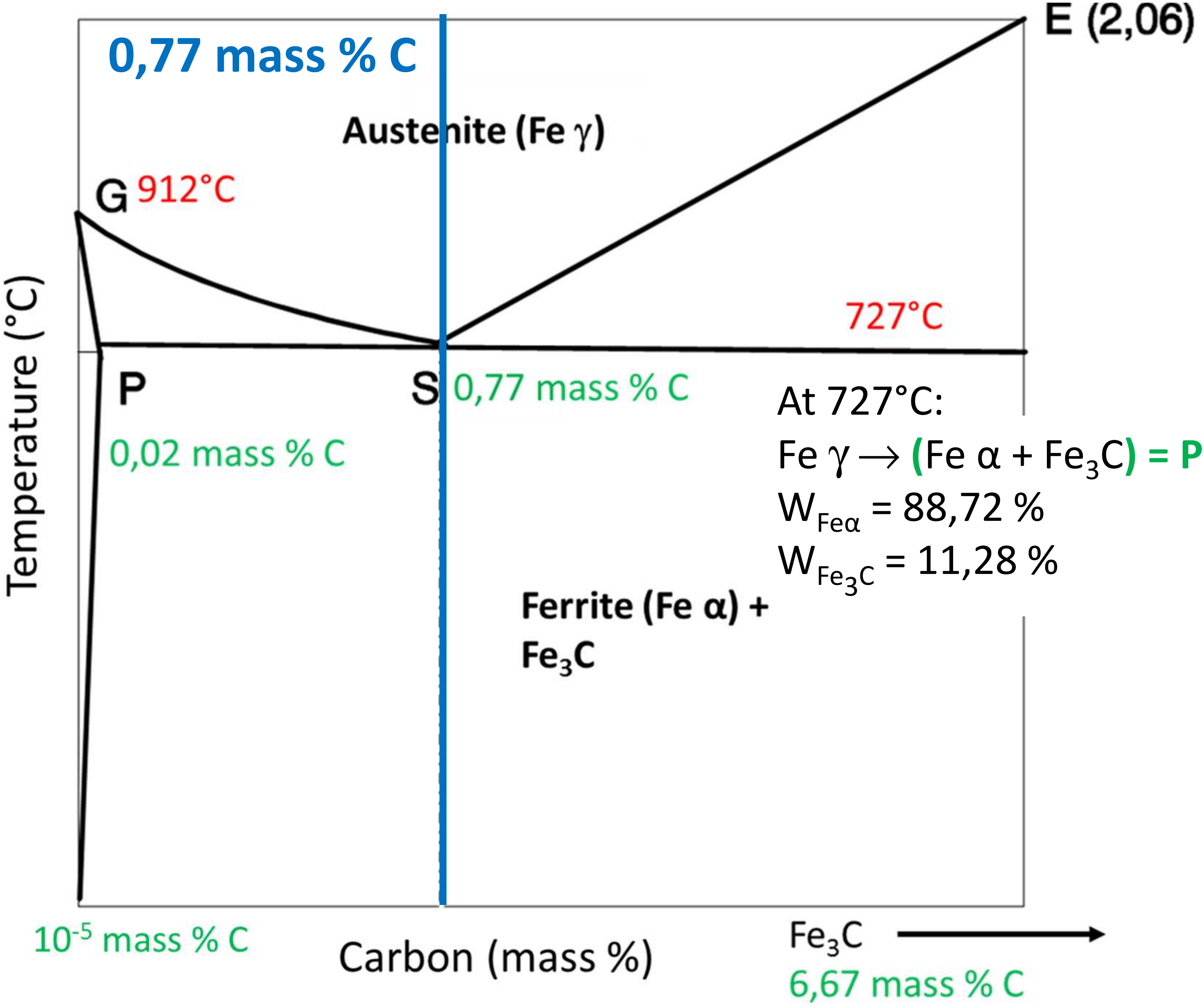


At 727°C: 100% Fe α (0,01 mass % C)

Cooling 727°C ⟶ Room Temperature:
Solubility of C in Fe α decreases
Excess C is rejected as Fe_3C
$W_{Fe_3C} = (0{,}01-10^{-5})/(6{,}67-10^{-5}) = 0{,}1\ \%$

[A.Mertens, ULg]

Eutectoid steel (0,77 mass % C)



At 727°C:

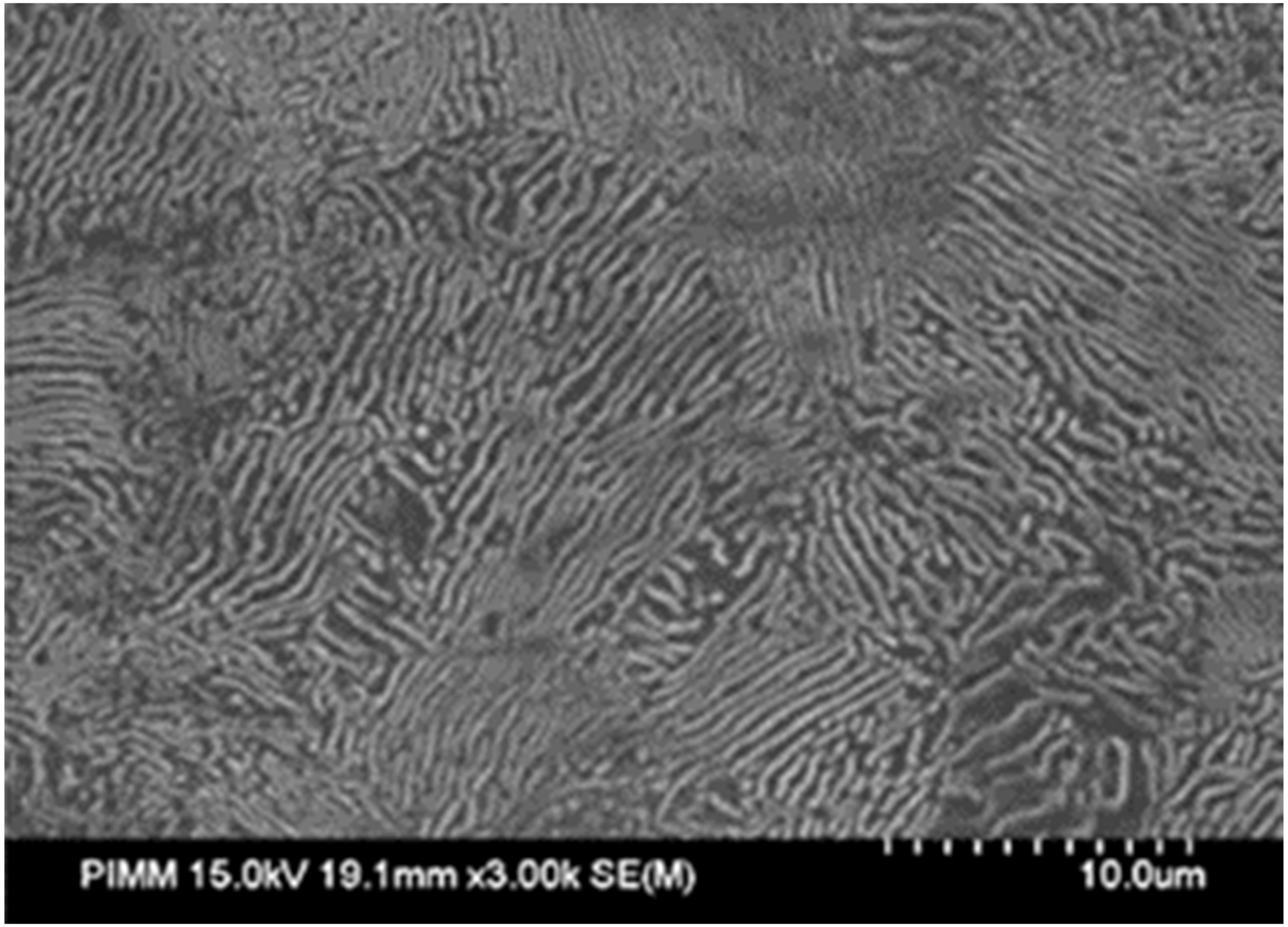
$\text{Fe}\,\gamma \rightarrow (\text{Fe}\,\alpha + \text{Fe}_3\text{C})$ **= Pearlite**

$W_{\text{Fe}\alpha} = 88{,}72\ \%$

$W_{\text{Fe}_3\text{C}} = 11{,}28\ \%$

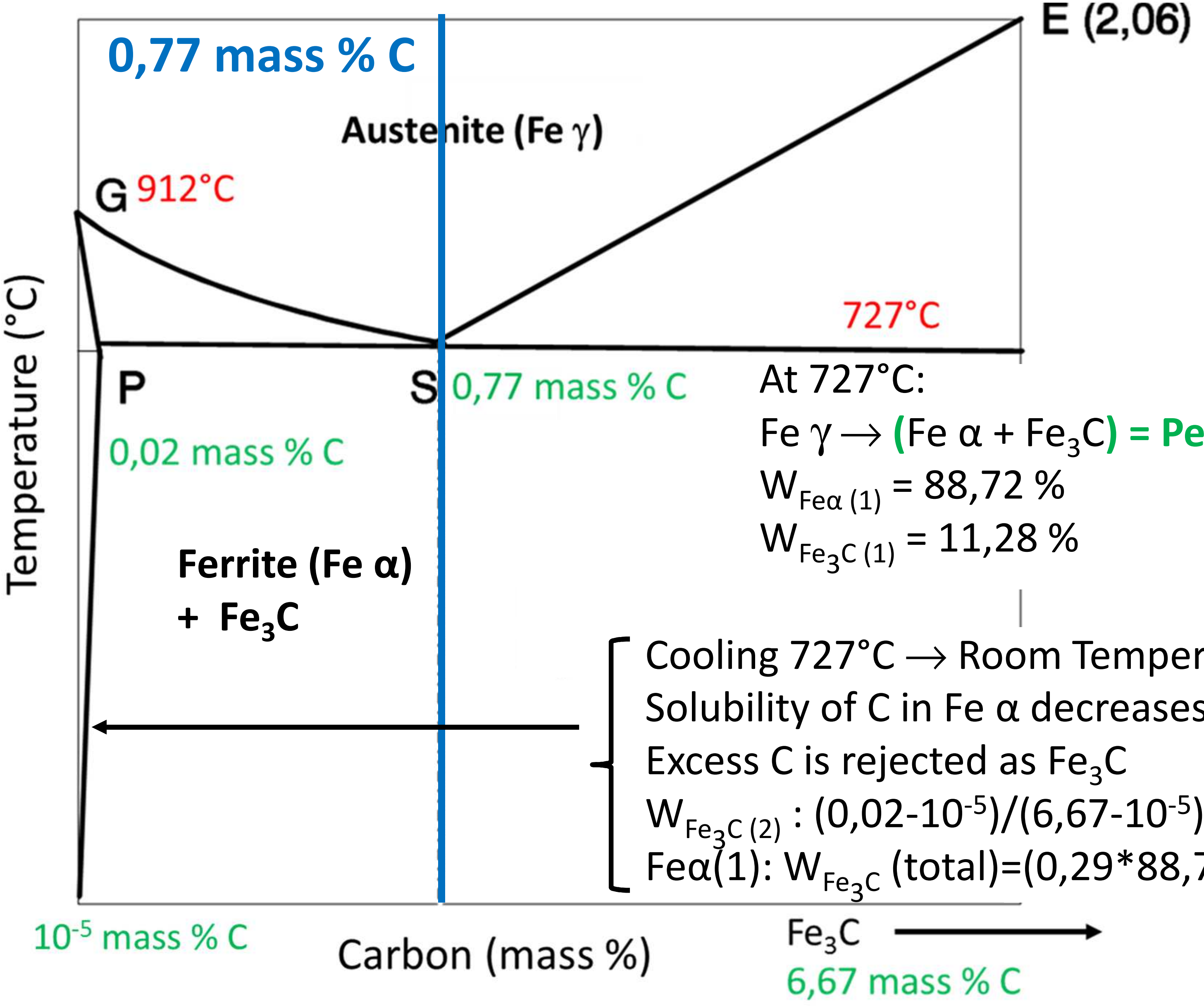
Eutectoid steel (0,77 mass % C)

Pearlite = Fe α + Fe_3C



[Baczmanski et al., MSF, 2014]

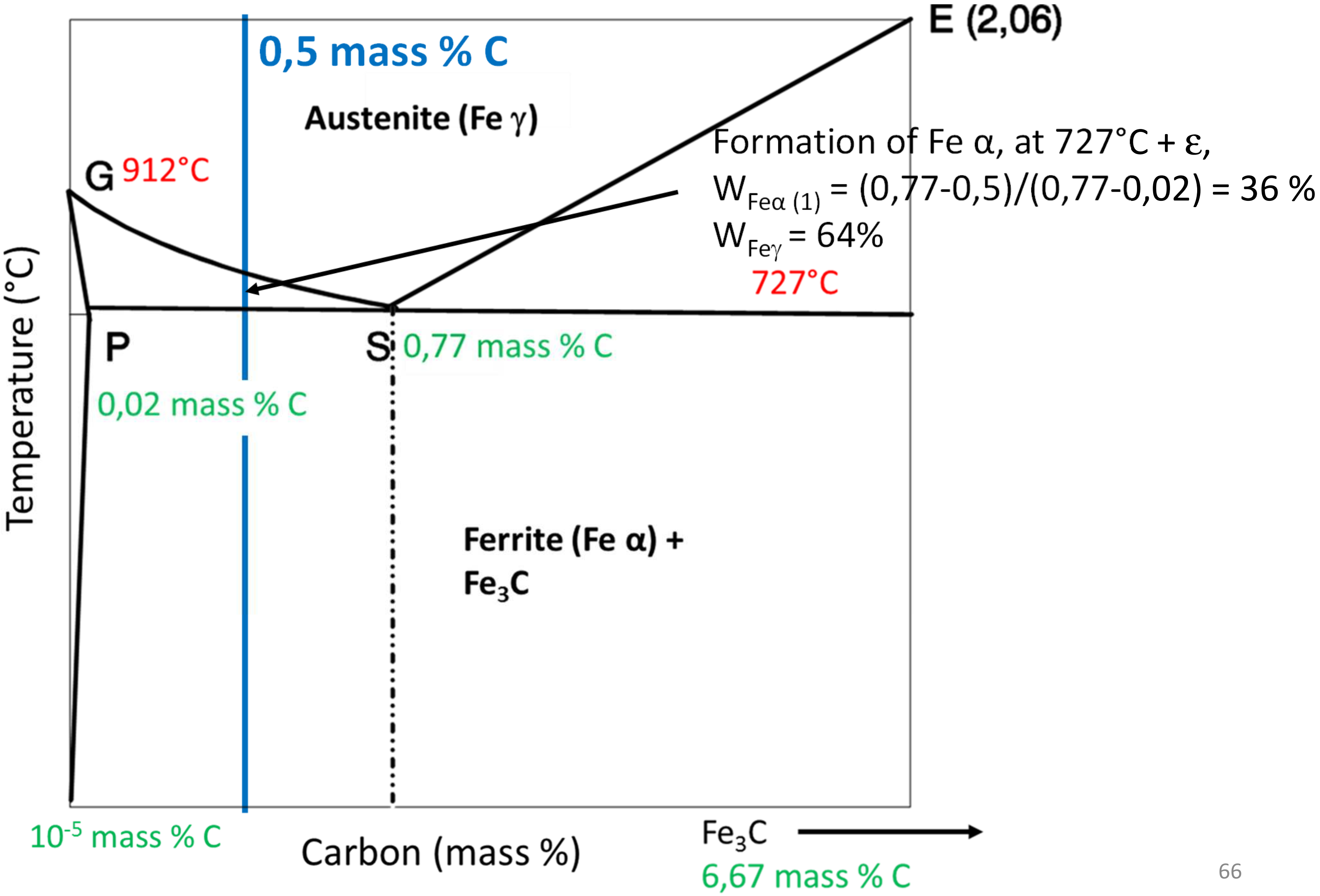
Eutectoid steel (0,77 mass % C)



At 727°C:
Fe γ → **(Fe α + Fe_3C) = Pearlite**
$W_{Fe\alpha\,(1)}$ = 88,72 %
$W_{Fe_3C\,(1)}$ = 11,28 %

Cooling 727°C → Room Temperature:
Solubility of C in Fe α decreases
Excess C is rejected as Fe_3C
$W_{Fe_3C\,(2)}$: $(0{,}02-10^{-5})/(6{,}67-10^{-5})$= 0,29% from
Feα(1): W_{Fe_3C} (total)=(0,29*88,72)+11,28=37%

Hypo-eutectoid steels

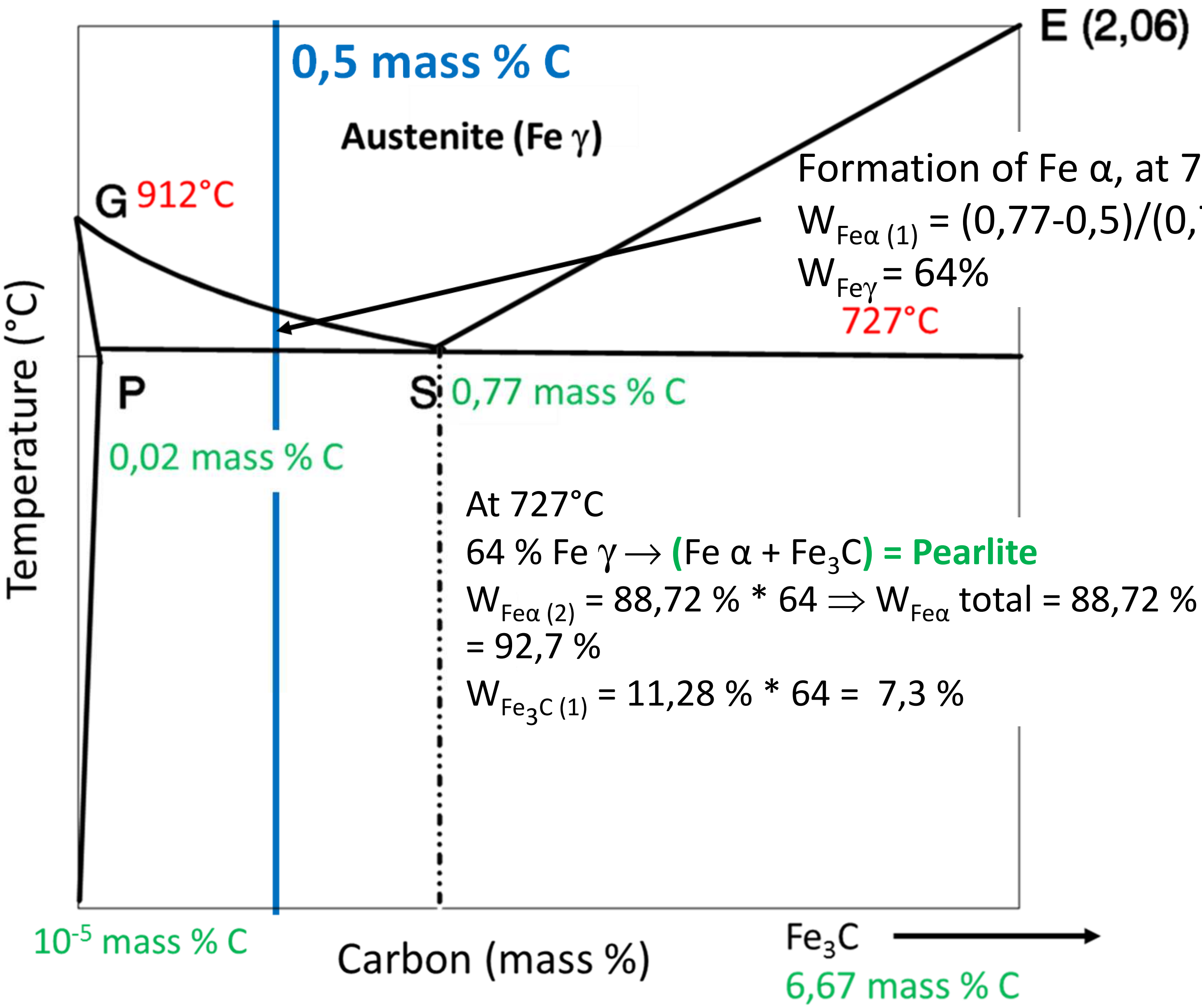


Formation of Fe α, at 727°C + ε,

$W_{Fe\alpha\ (1)} = (0{,}77-0{,}5)/(0{,}77-0{,}02) = 36\ \%$

$W_{Fe\gamma} = 64\%$

Hypo-eutectoid steels



Formation of Fe α, at 727°C + ε,

$W_{Fe\alpha\,(1)}$ = (0,77-0,5)/(0,77-0,02) = 36 %

$W_{Fe\gamma}$ = 64%

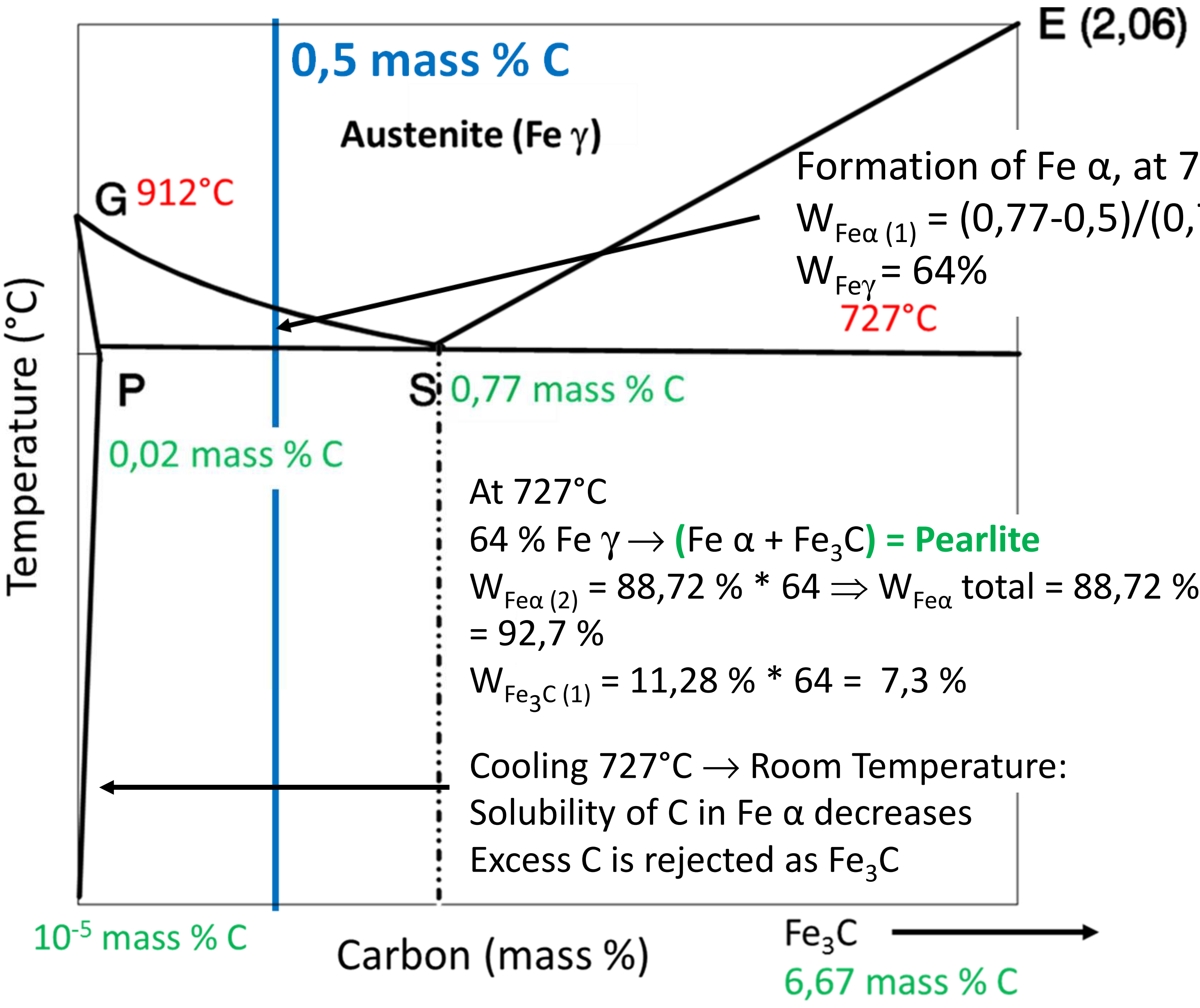
At 727°C

64 % Fe γ ⟶ (Fe α + Fe_3C) = **Pearlite**

$W_{Fe\alpha\,(2)}$ = 88,72 % * 64 ⇒ $W_{Fe\alpha}$ total = 88,72 % * 64 + 36 = 92,7 %

$W_{Fe_3C\,(1)}$ = 11,28 % * 64 = 7,3 %

Hypo-eutectoid steels



Formation of Fe α, at 727°C + ε,
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64 % Fe γ ⟶ **(Fe α + Fe_3C) = Pearlite**
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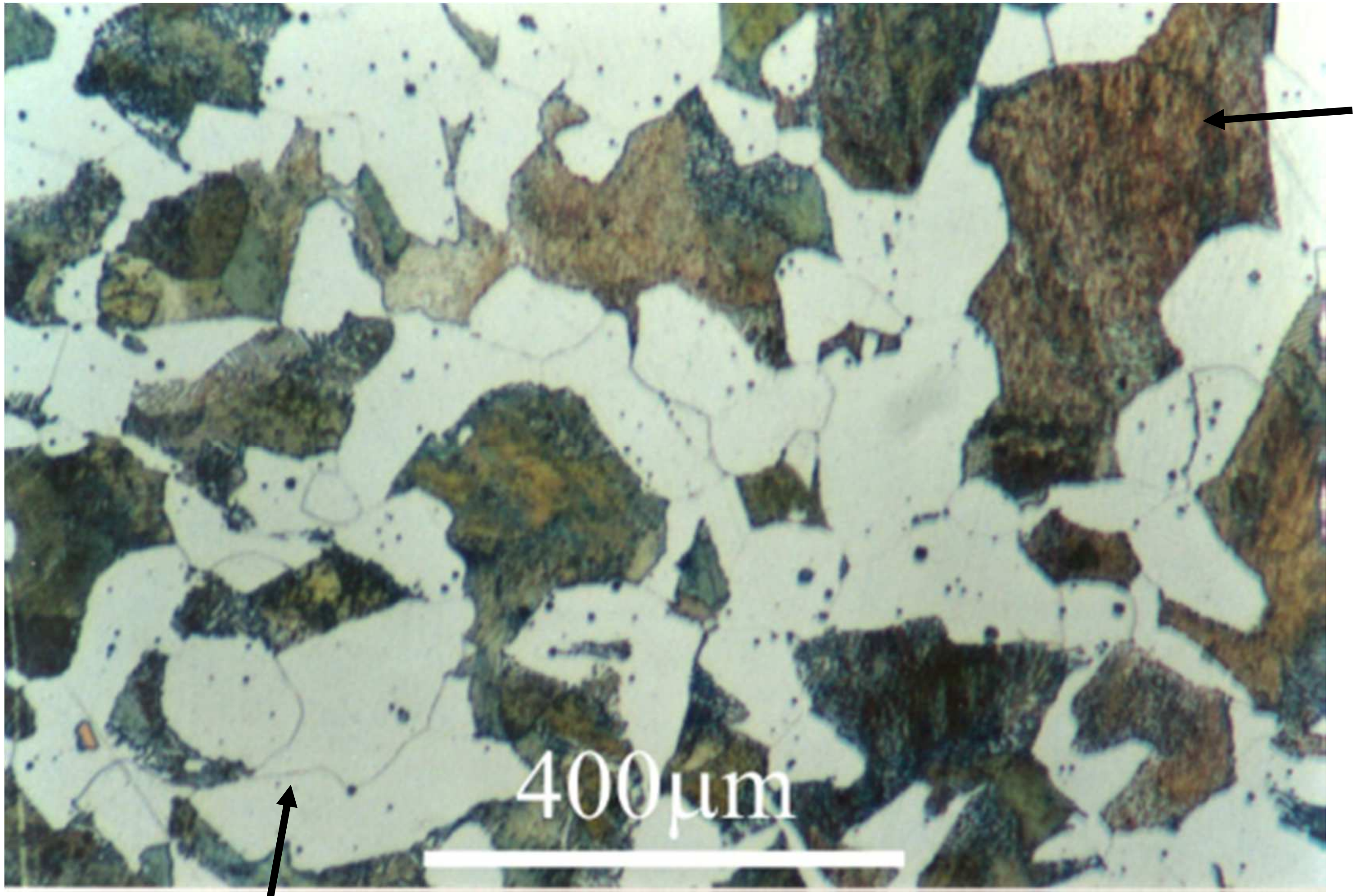
Cooling 727°C ⟶ Room Temperature:
Solubility of C in Fe α decreases
Excess C is rejected as Fe_3C

Hypo-eutectoid steels

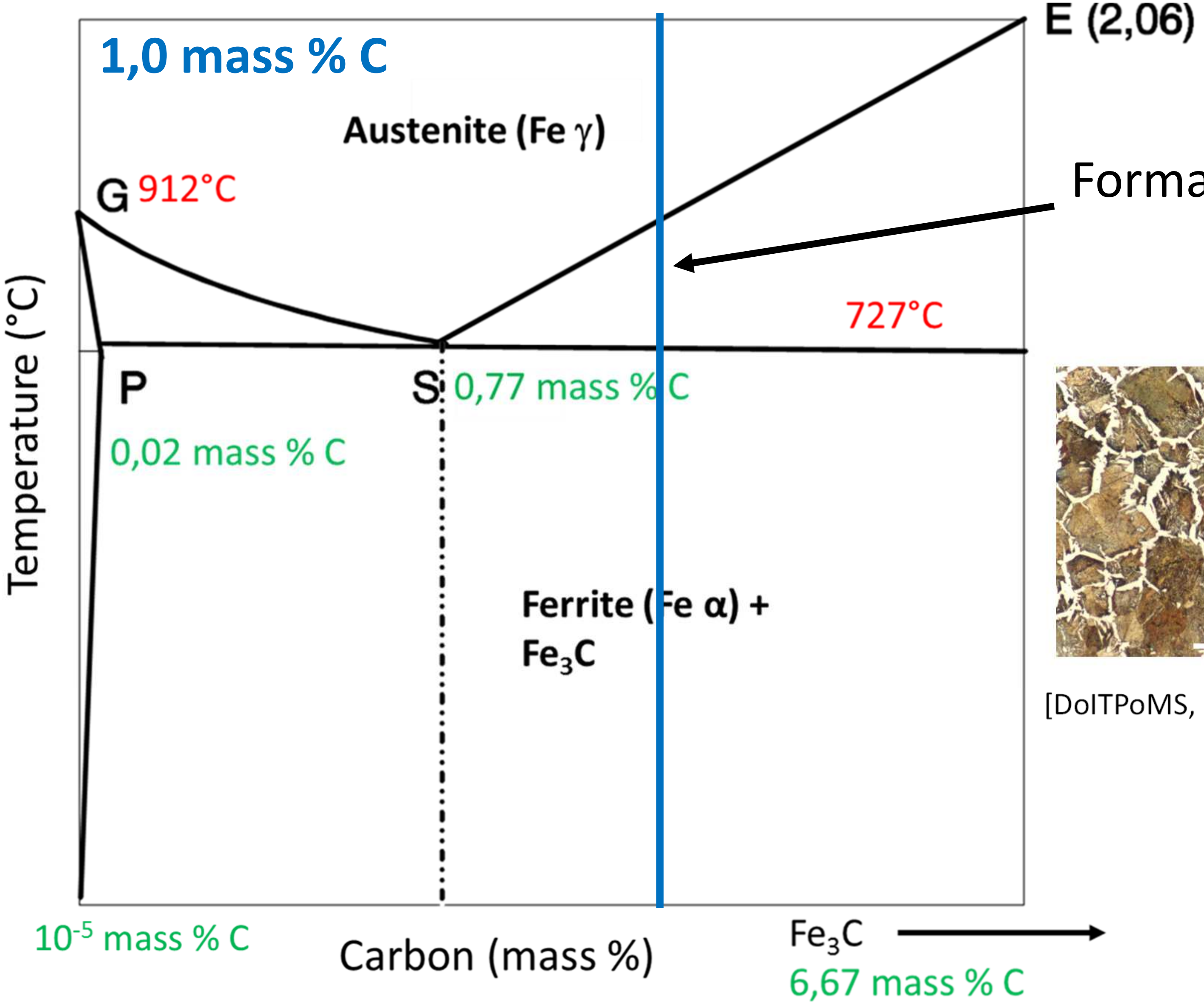


Pearlite

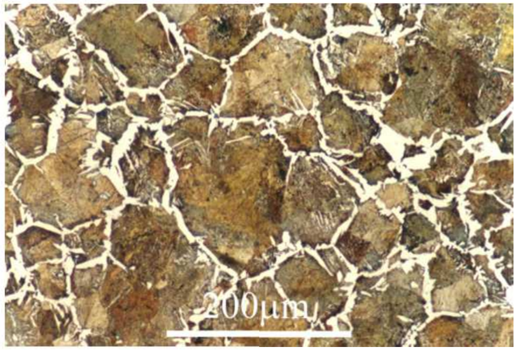
Pro-eutectoid Fe α

[DoITPoMS, University of Cambridge]

Hyper-eutectoid steels



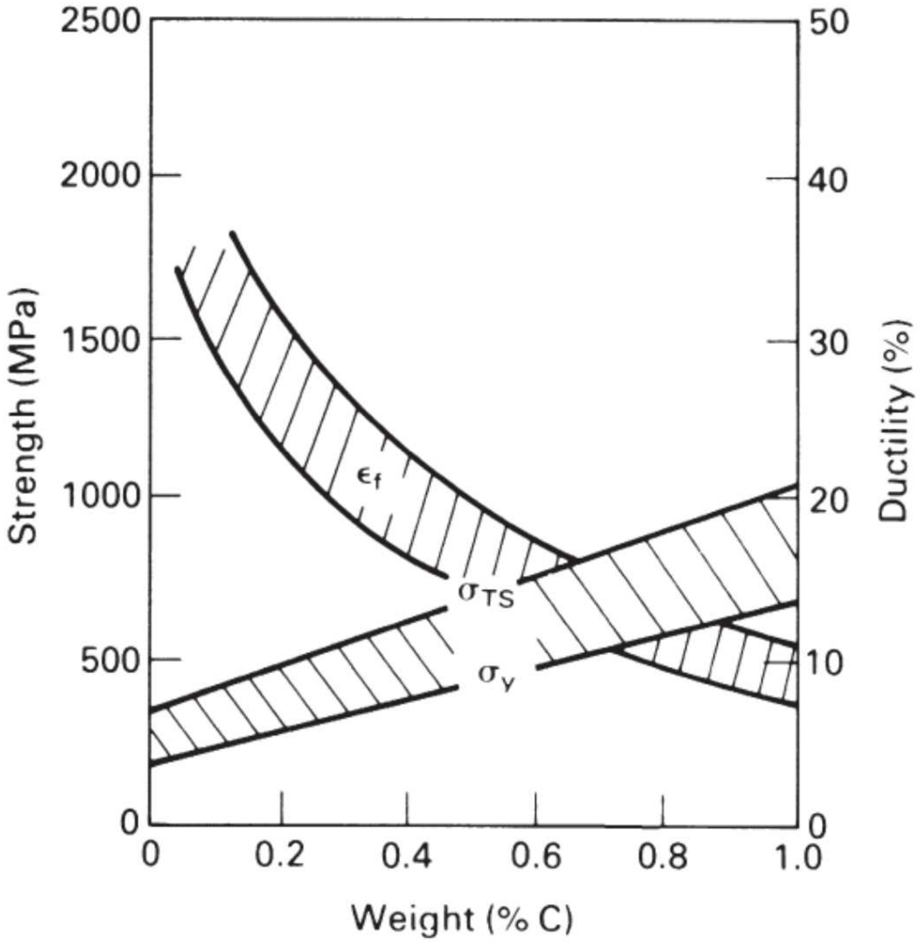
Formation of Fe_3C



[DoITPoMS, University of Cambridge]

Normalised carbon steels

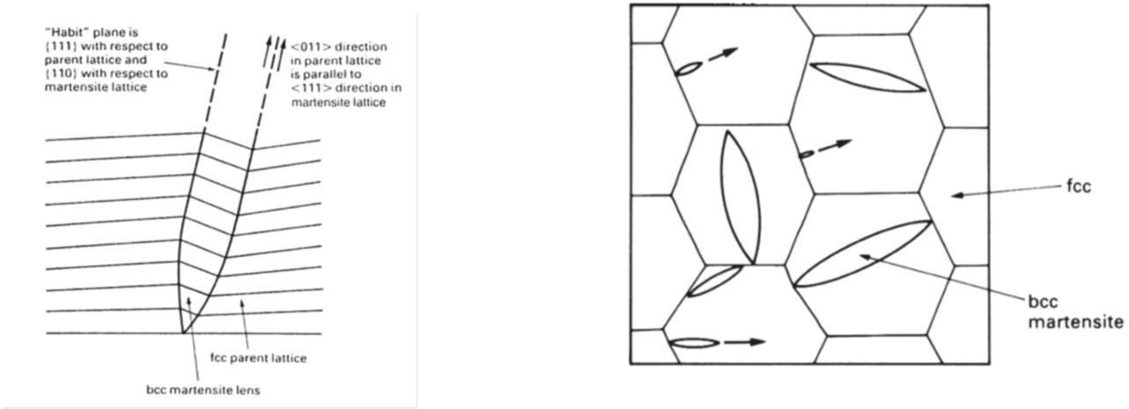
- Mechanical properties
  - **Strength ↑ with C ↑:** Fe_3C acts as strengthening phase
  - **Ductility ↓ with C ↑:** α - Fe_3C interfaces act as nucleation sites for cracks



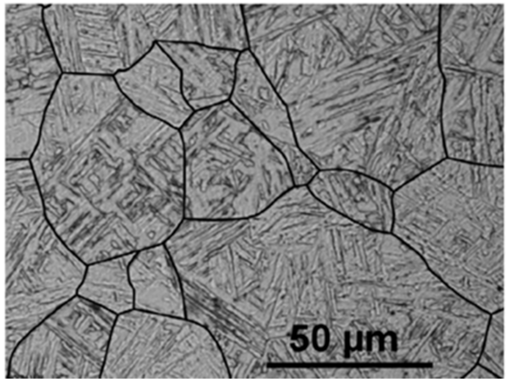
[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

And after fast cooling from austenite?

- **Martensite** = metastable phase that forms after **fast cooling** (quench) of C steel
- It forms by a **displacive** mechanism.
- It is very **hard** and **brittle**.
- It has a typical acicular morphology



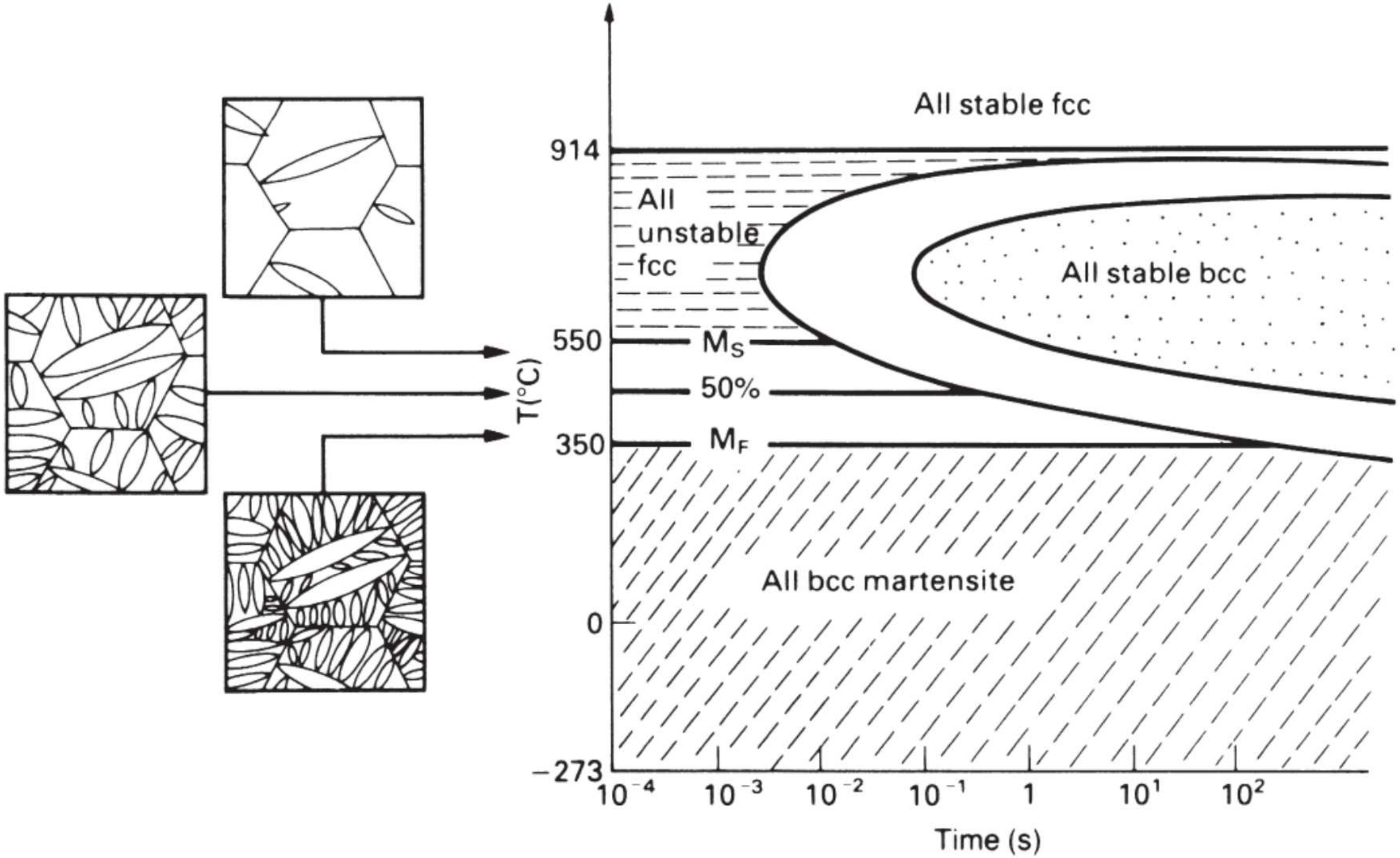
[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]



[Christien et al., Mater. Char., 2013]

Quenched and tempered carbon steels (1)

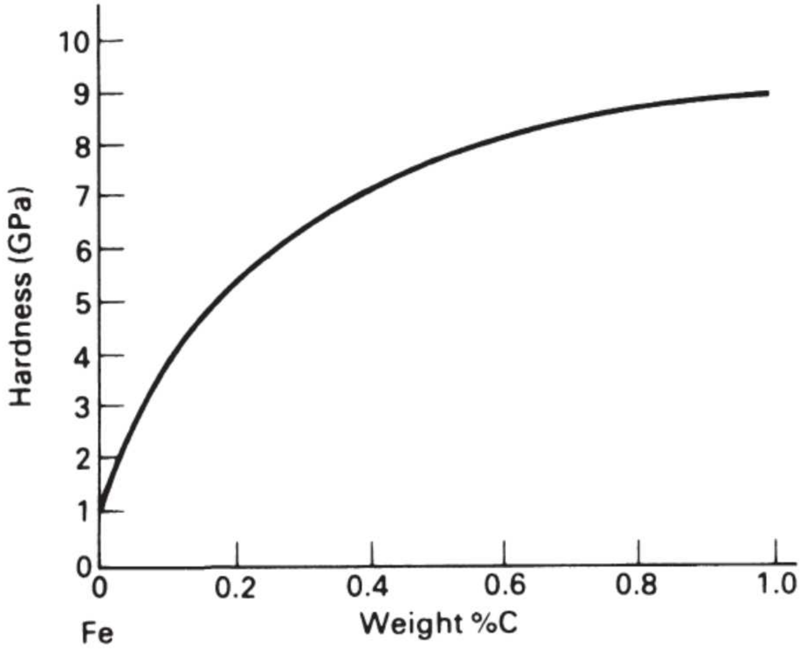
- Fast cooling ⇒ martensitic transformation

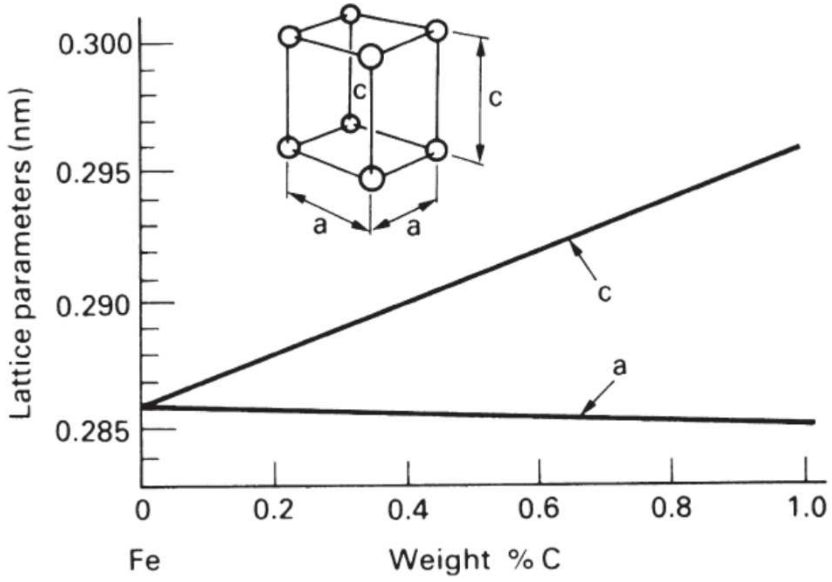


[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

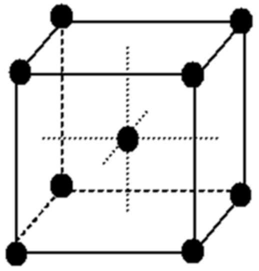
Quenched and tempered carbon steels (2)

- Martensite is very hard, due to Carbon supersaturation...
- ... but also **brittle**.





Lattice distortion ↑ when carbon ↑

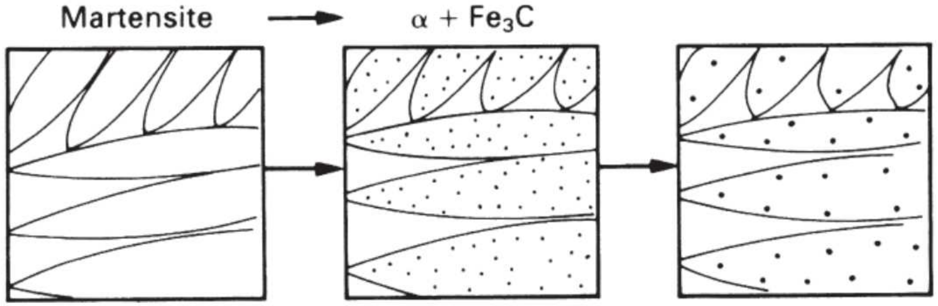


BCC

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

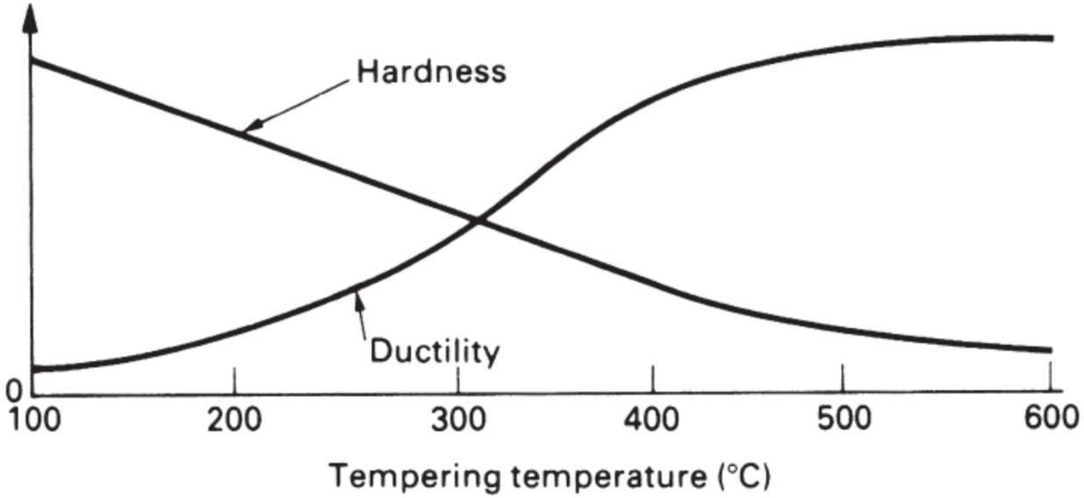
Quenched and tempered carbon steels (3)

- Tempering restores some ductility



Supersaturated C precipitates out as Fe_3C (small particles)

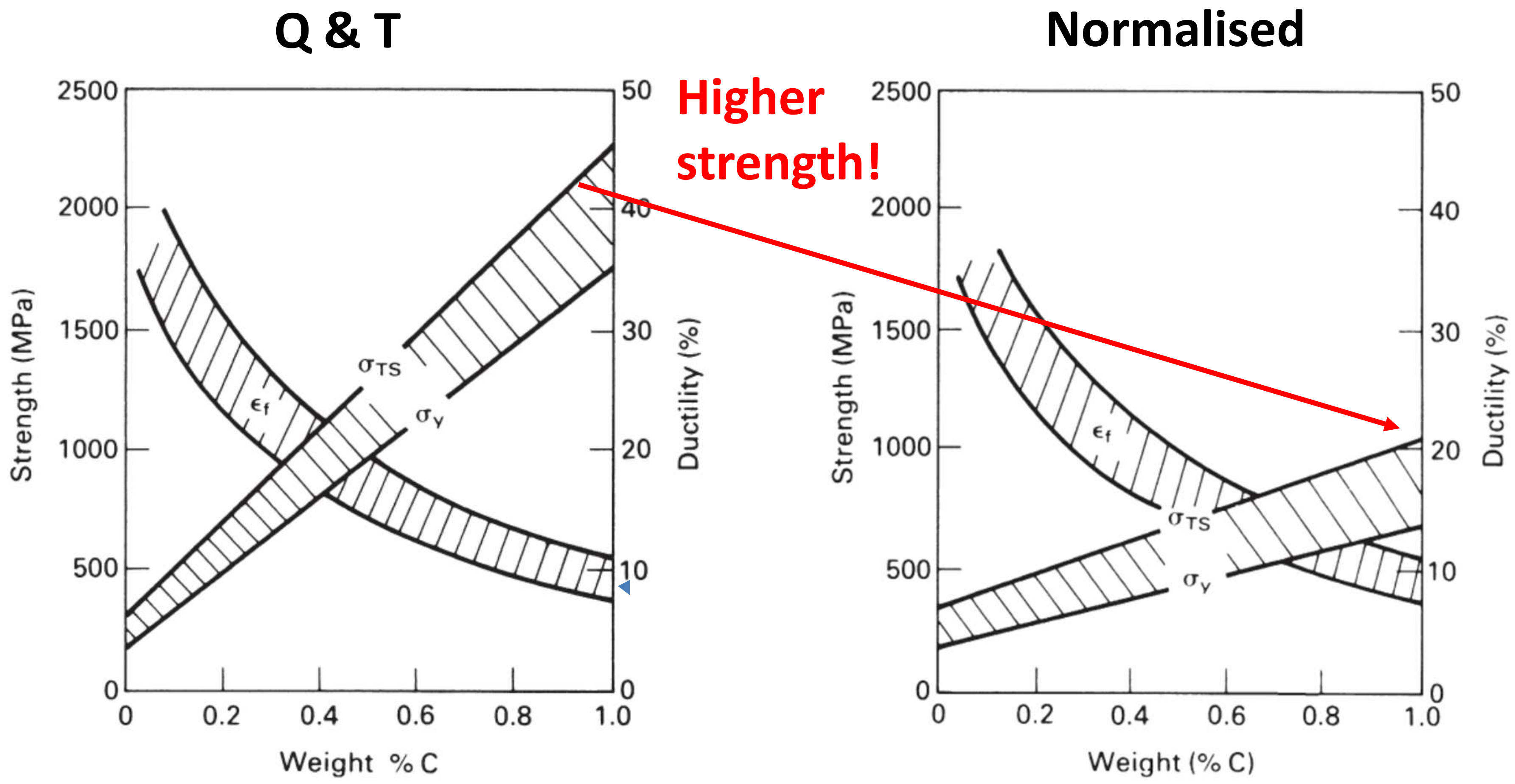
Reheating in "medium" temperature range



[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Quenched and tempered carbon steels (4)

- Mechanical properties



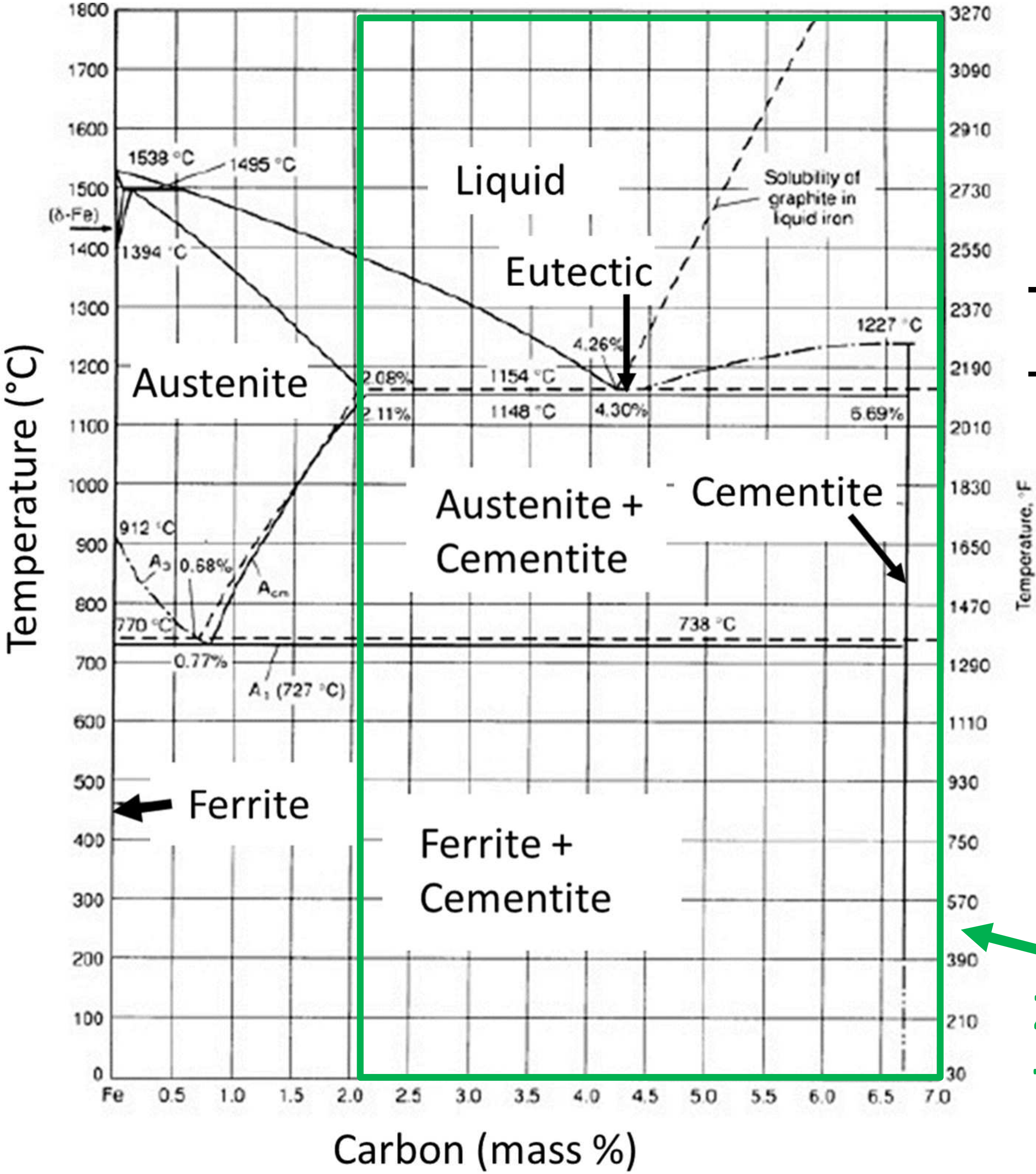
Q & T

Normalised

Higher strength!

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Cast Irons (1)



—— Metastable, Fe-Fe$_3$C

- - - Stable, Fe-C graphite

C content > 2 mass % C:
cast iron
Transition between the stable and metastable Fe-C diagrams

Zone of interest for cast iron

Cast Irons (2)

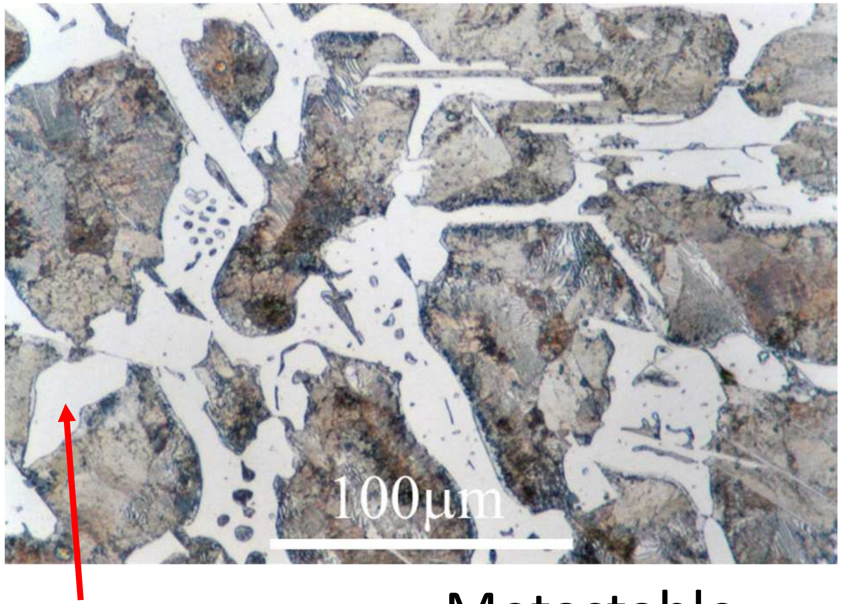
Grey

Graphite

Stable Fe-C diagram

[http://core.materials.ac.uk/search/detail.php?id=1416]

White



Fe_3C

Metastable Fe-C diagram

[http://core.materials.ac.uk/search/detail.php?id=1408]

Outline

- Introduction
- Light alloys
- Carbon steels
- Alloy steels
  - Low alloy, stainless or tool steels
- Production, forming and joining of metals

Alloy steels

Low alloy, stainless or tool steels

Role of alloying elements (1)

Alloying elements may modify

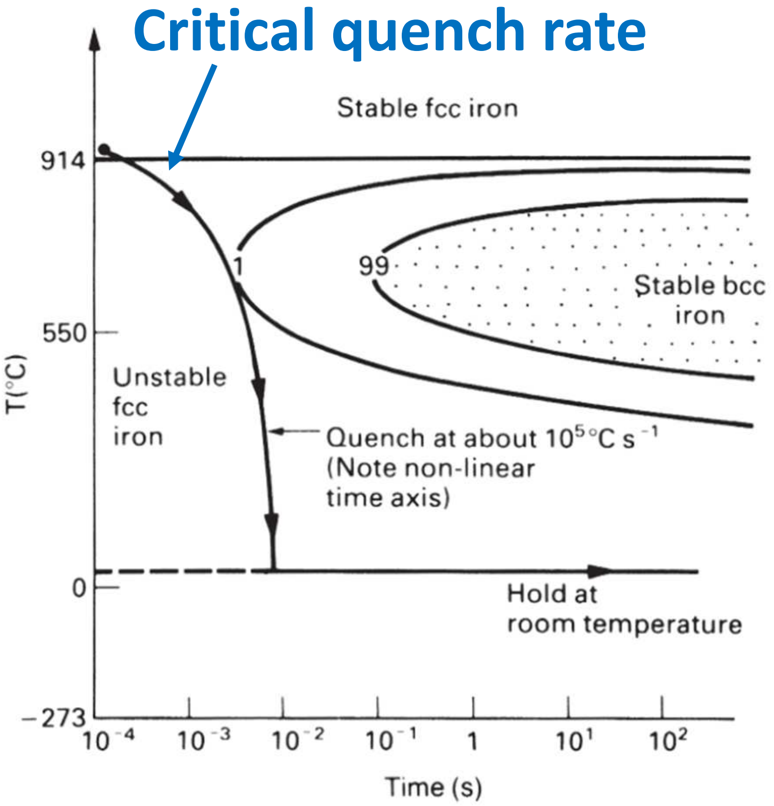
- Hardenability
- Strength, hardness
- Corrosion resistance
- Equilibrium structure (phases)

Hardenability

= Ease to form a fully martensitic structure

For a displacive transformation to occur, diffusive transformation should not take place!

TTT Diagram

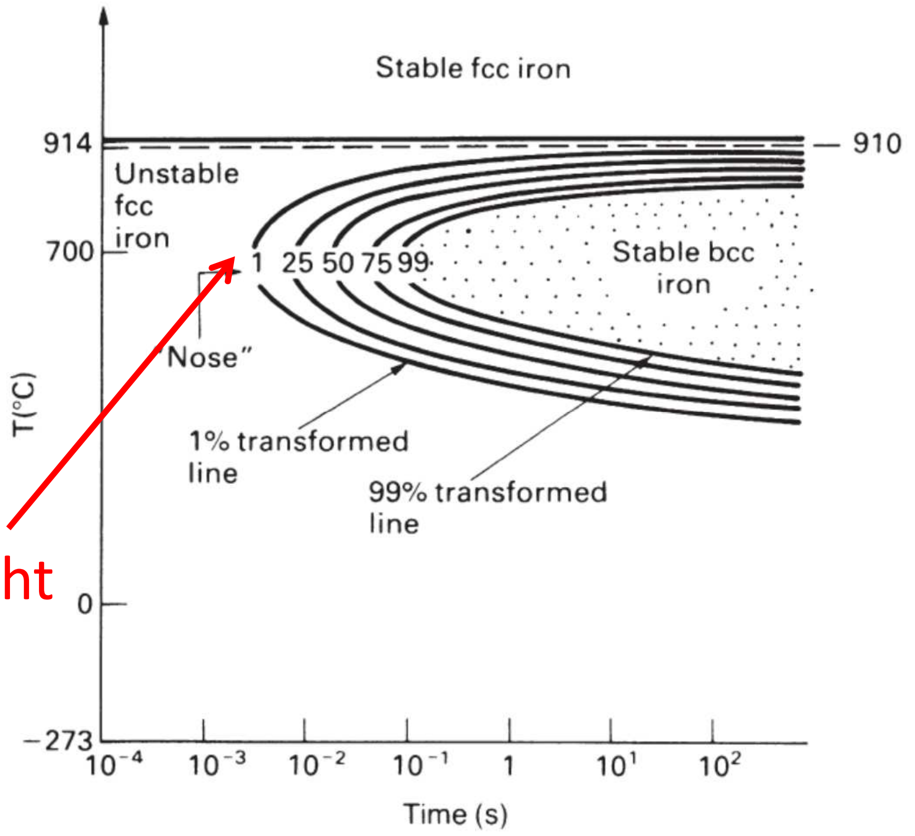


[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Hardenability

= Ease to form a fully martensitic structure

TTT Diagram

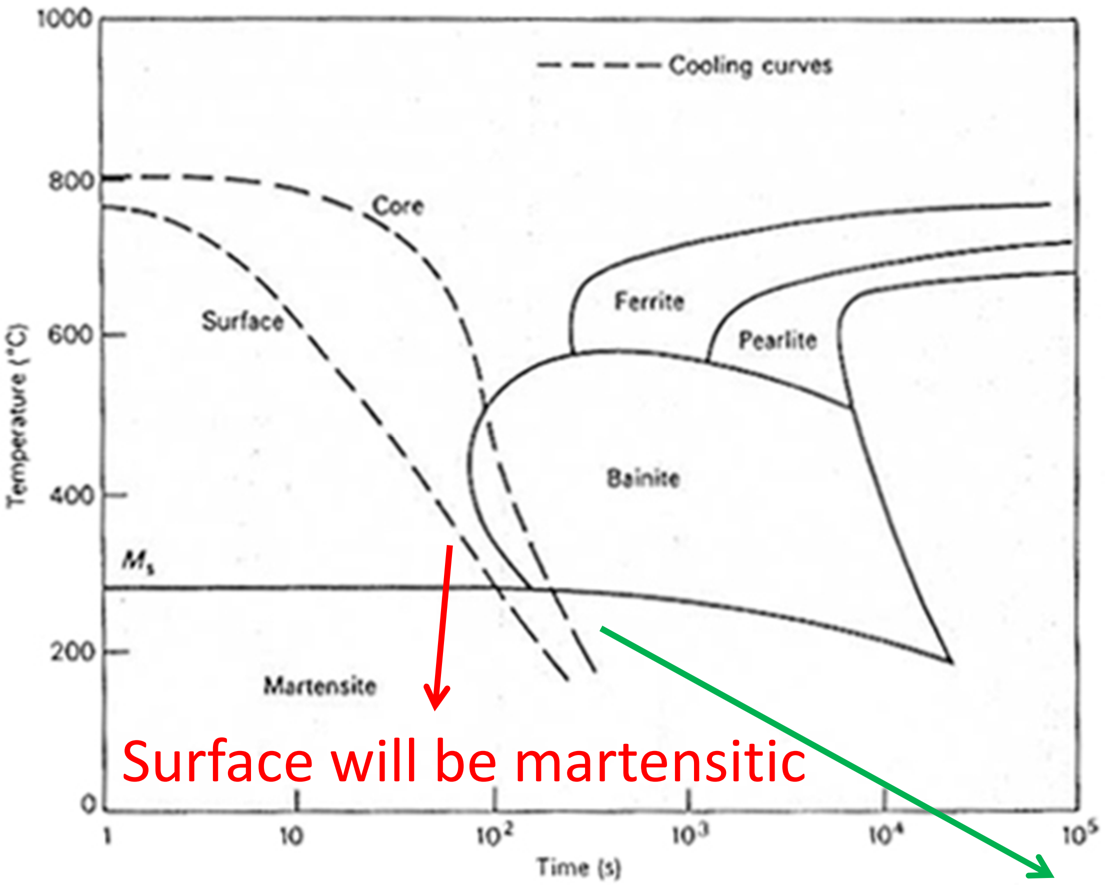


High hardenability
→ shifting the "C" curves to the right
→ Critical quenching rate ↓

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Hardenability of large components ?

Oil quench on a bar with diameter = 95 mm



Surface will be martensitic

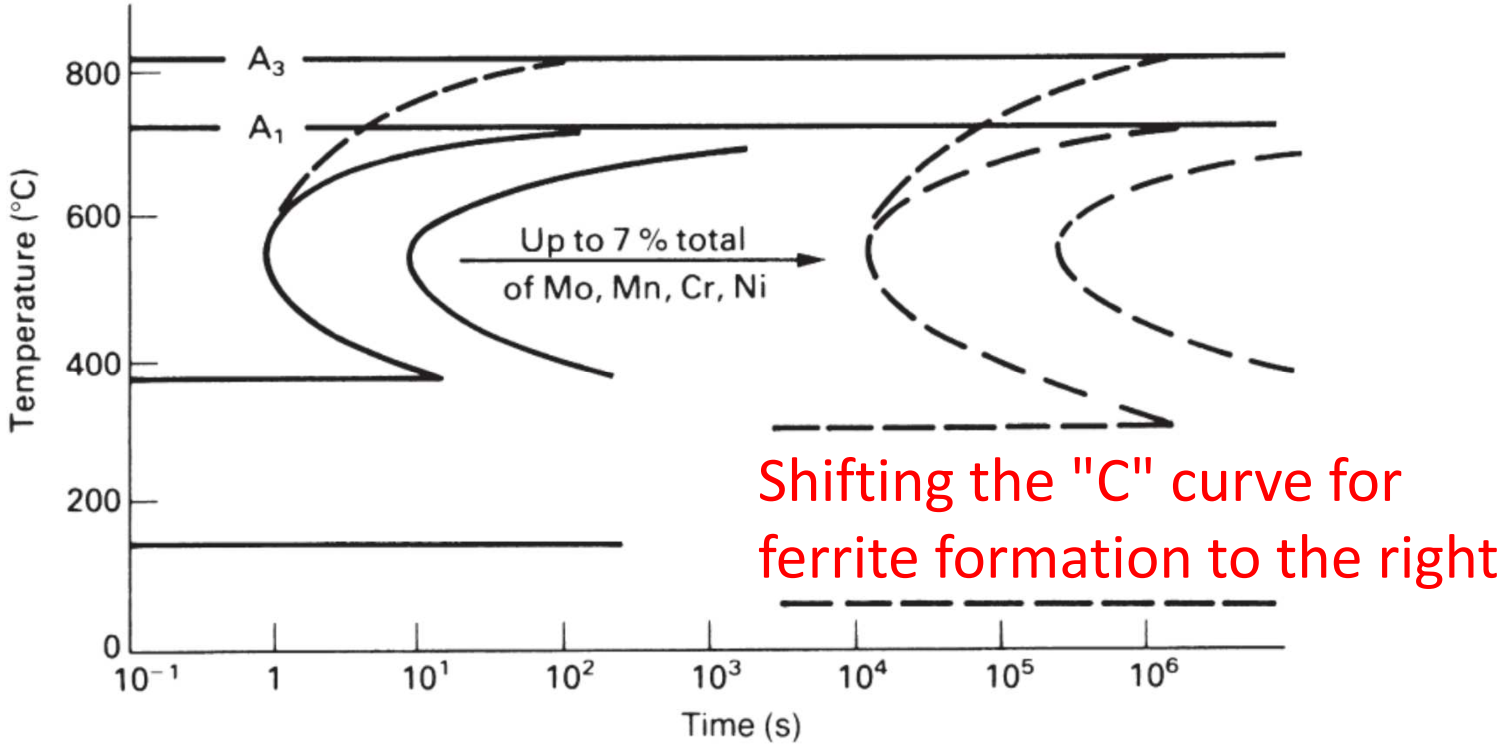
Core will be (partially) bainitic

Risk of hetereogeneous structures for large components

[http://www.totalmateria.com/articles/Art146.htm]

Role of alloying elements (2)

- Improve hardenability (Mo, Mn, Cr, Ni...)



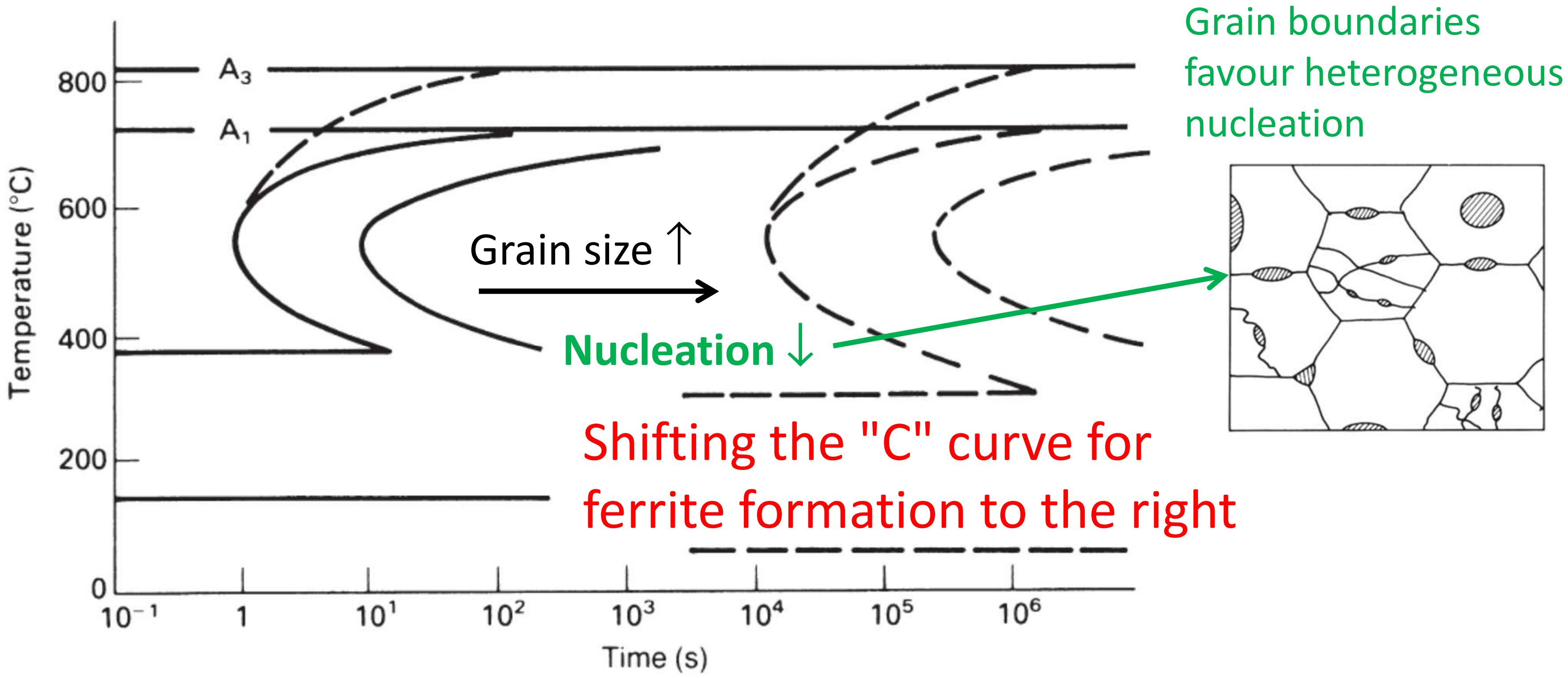
Shifting the "C" curve for ferrite formation to the right

⇒ Make it easier to obtain martensite even for **large** components

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Effect of grain size

- Hardenability also changes with grain size



Grain boundaries favour heterogeneous nucleation

Grain size ↑

Nucleation ↓

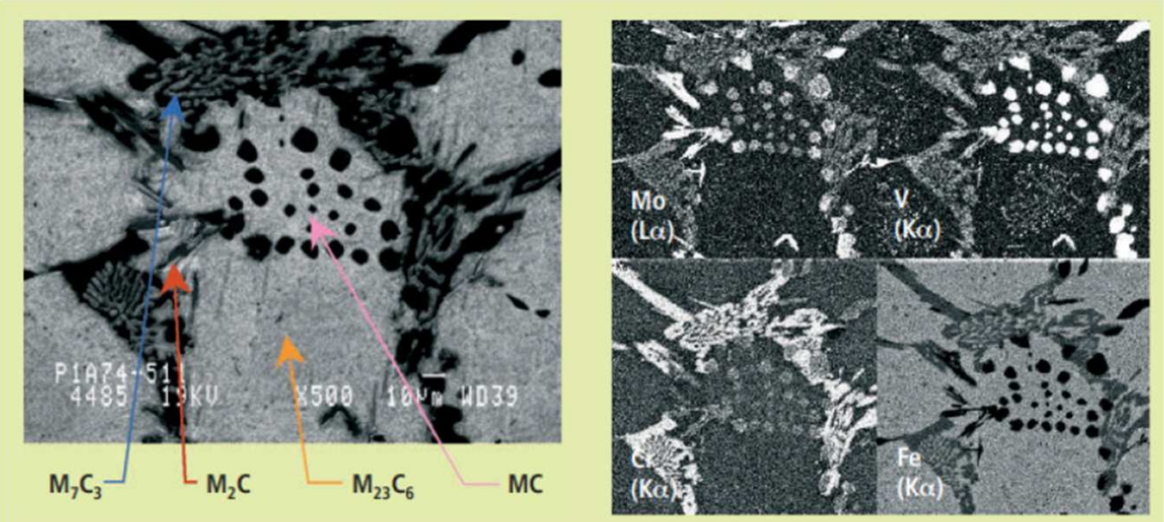
Shifting the "C" curve for ferrite formation to the right

⇒ Make it easier to obtain martensite even for **large** components

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Role of alloying elements (3)

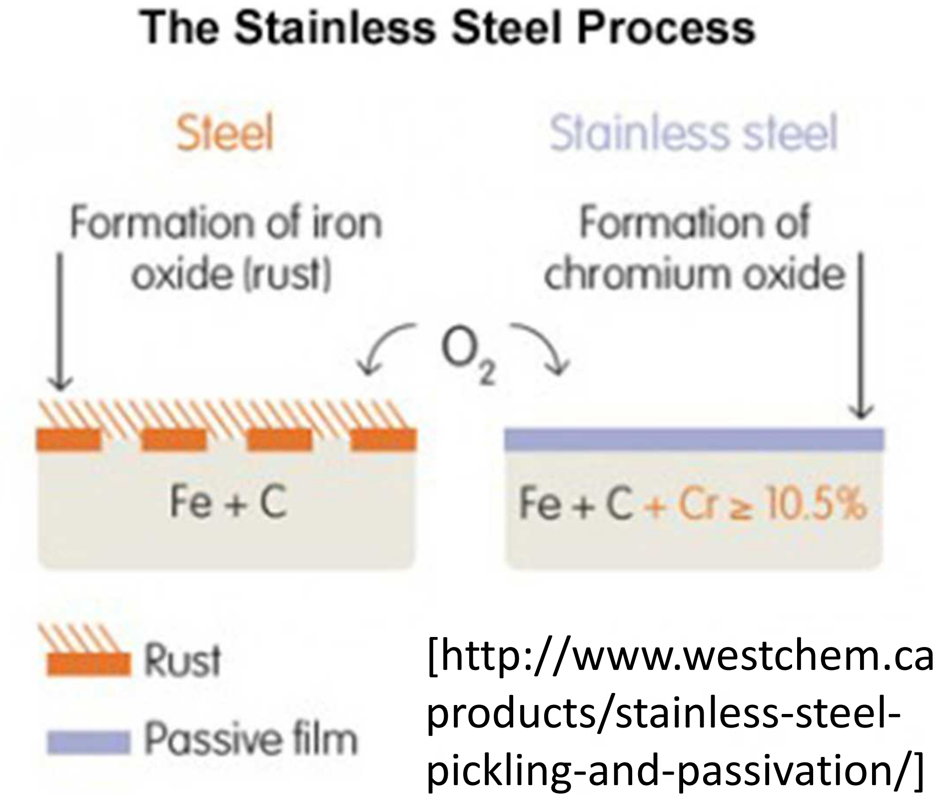
- Strengthening:
  - Solid solution
  - Precipitation
- Tool steels:
  - Dissolved W, Co
- High Speed Steels (V, W, Mo, Cr)
  - Alloyed carbides: VC, Mo_2C, WC, $Cr_{23}C_6$



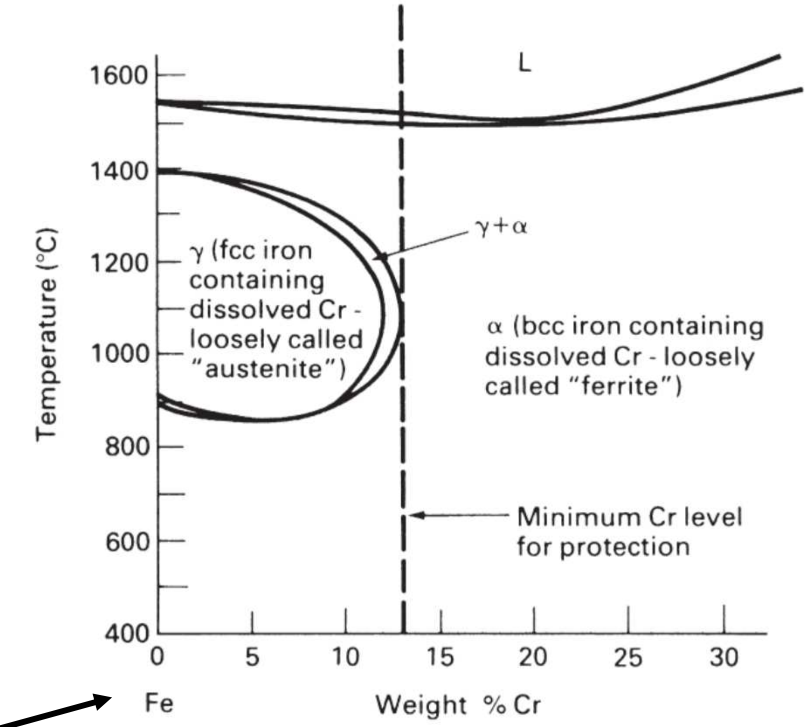
[J.T.Tchuindjang, ULg, 2005]

Role of alloying elements (4)

- Corrosion resistance, Cr in stainless steels
  $\Rightarrow$ passivating layer of Cr_2O_3



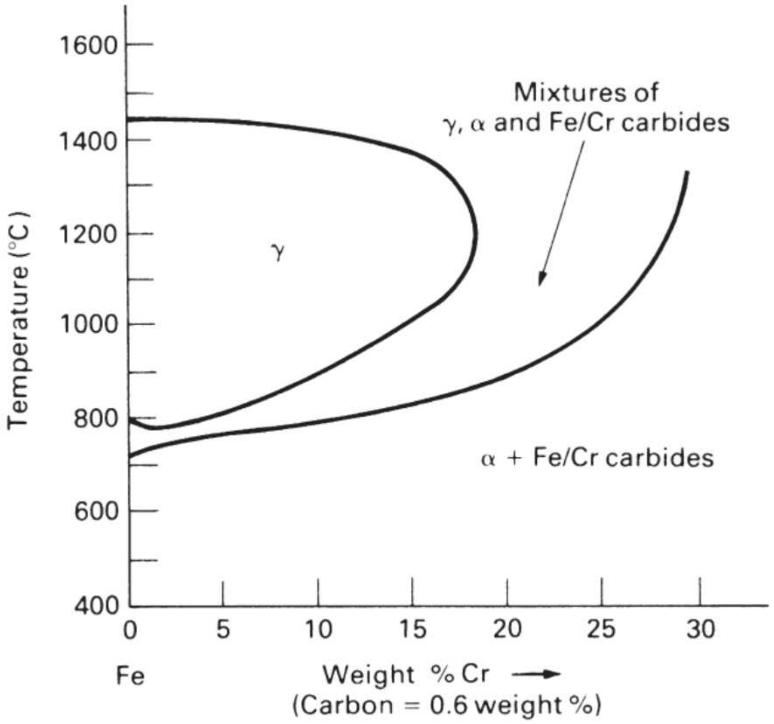
[http://www.westchem.ca/products/stainless-steel-pickling-and-passivation/]



- Cr stabilizes ferrite

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Role of alloying elements (5)



- Corrosion resistance,
  Cr in stainless steels ⇒
  passivating layer of Cr_2O_3
- Cr stabilizes ferrite

⇒ Other alloying elements are added to modify the structure of stainless steels

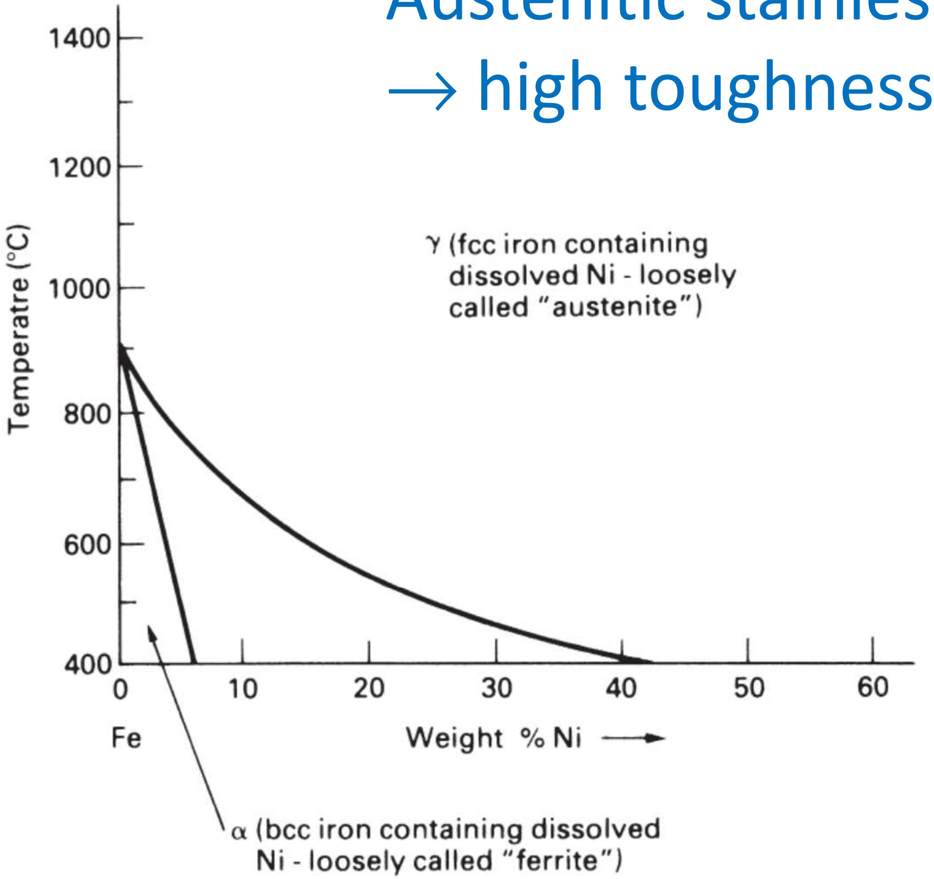
Increasing C content to make hardenable stainless steels

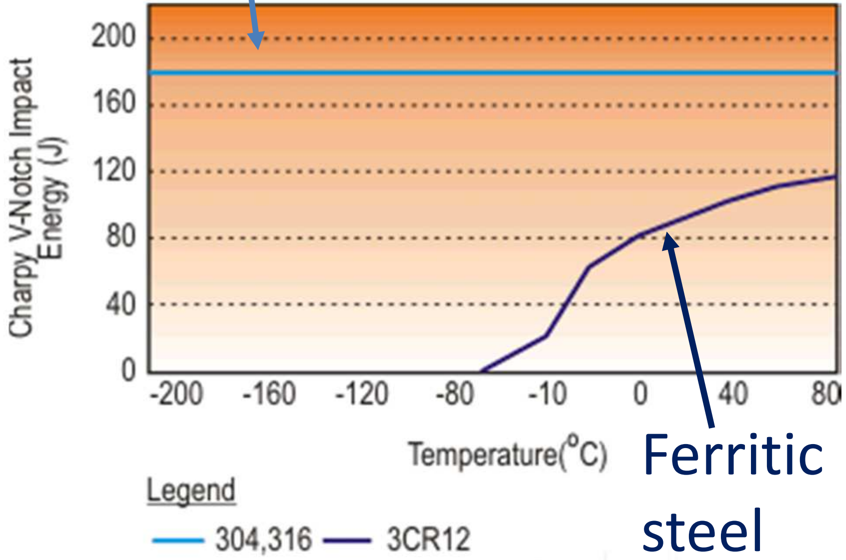
[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Role of alloying elements (6)

- Ni is added in stainless steels to stabilize austenite

Austenitic stainless steels
→ high toughness at low T





Ferritic steel

[https://www.azom.com/article.aspx?ArticleID=1176]

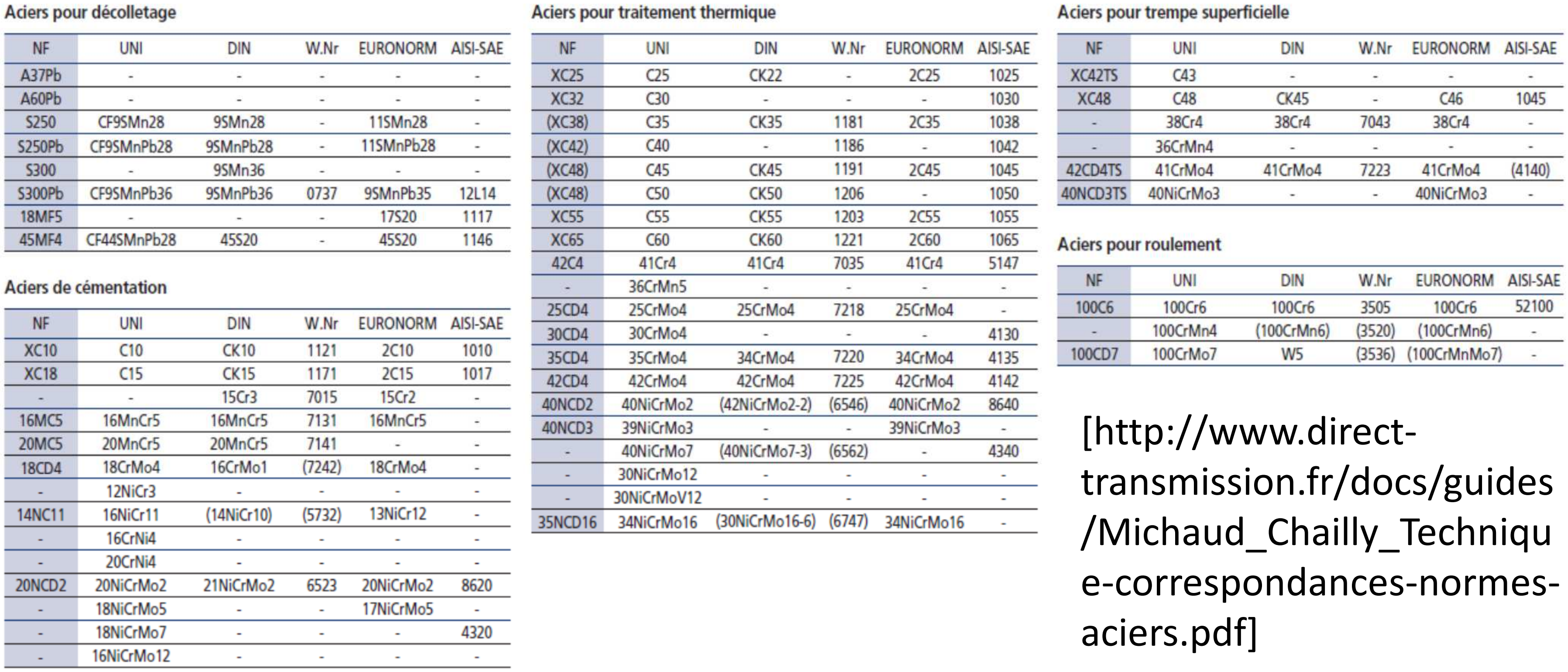
[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Standard designations of steels (1)

- Most used: American Iron and Steel Institute (AISI) and Society of Automotive Engineers (SAE)
- Four digits
  - First two digits: Type of steel
  - Last two digits: amount of carbon
- Examples:
  - AISI 1020: plain carbon steel (10) with 0,2 wt% C (20)
  - AISI 4340: Ni-Cr-Mo steel (43) with 0,4 wt% C (40)
- See https://www.engineeringtoolbox.com/aisi-sae-steel-numbering-system-d_1449.html

Standard designations of steels (2)

- Other classifications: German (DIN), French (AFNOR)...
- Table of correspondance:



Aciers pour décolletage

NF	UNI	DIN	W.Nr	EURONORM	AISI-SAE
A37Pb	-	-	-	-	-
A60Pb	-	-	-	-	-
S250	CF9SMn28	9SMn28	-	11SMn28	-
S250Pb	CF9SMnPb28	9SMnPb28	-	11SMnPb28	-
S300	-	9SMn36	-	-	-
S300Pb	CF9SMnPb36	9SMnPb36	0737	9SMnPb35	12L14
18MF5	-	-	-	17S20	1117
45MF4	CF44SMnPb28	45S20	-	45S20	1146

Aciers de cémentation

NF	UNI	DIN	W.Nr	EURONORM	AISI-SAE
XC10	C10	CK10	1121	2C10	1010
XC18	C15	CK15	1171	2C15	1017
-	-	15Cr3	7015	15Cr2	-
16MC5	16MnCr5	16MnCr5	7131	16MnCr5	-
20MC5	20MnCr5	20MnCr5	7141	-	-
18CD4	18CrMo4	16CrMo1	(7242)	18CrMo4	-
-	12NiCr3	-	-	-	-
14NC11	16NiCr11	(14NiCr10)	(5732)	13NiCr12	-
-	16CrNi4	-	-	-	-
-	20CrNi4	-	-	-	-
20NCD2	20NiCrMo2	21NiCrMo2	6523	20NiCrMo2	8620
-	18NiCrMo5	-	-	17NiCrMo5	-
-	18NiCrMo7	-	-	-	4320
-	16NiCrMo12	-	-	-	-

Aciers pour traitement thermique

NF	UNI	DIN	W.Nr	EURONORM	AISI-SAE
XC25	C25	CK22	-	2C25	1025
XC32	C30	-	-	-	1030
(XC38)	C35	CK35	1181	2C35	1038
(XC42)	C40	-	1186	-	1042
(XC48)	C45	CK45	1191	2C45	1045
(XC48)	C50	CK50	1206	-	1050
XC55	C55	CK55	1203	2C55	1055
XC65	C60	CK60	1221	2C60	1065
42C4	41Cr4	41Cr4	7035	41Cr4	5147
-	36CrMn5	-	-	-	-
25CD4	25CrMo4	25CrMo4	7218	25CrMo4	-
30CD4	30CrMo4	-	-	-	4130
35CD4	35CrMo4	34CrMo4	7220	34CrMo4	4135
42CD4	42CrMo4	42CrMo4	7225	42CrMo4	4142
40NCD2	40NiCrMo2	(42NiCrMo2-2)	(6546)	40NiCrMo2	8640
40NCD3	39NiCrMo3	-	-	39NiCrMo3	-
-	40NiCrMo7	(40NiCrMo7-3)	(6562)	-	4340
-	30NiCrMo12	-	-	-	-
-	30NiCrMoV12	-	-	-	-
35NCD16	34NiCrMo16	(30NiCrMo16-6)	(6747)	34NiCrMo16	-

Aciers pour trempe superficielle

NF	UNI	DIN	W.Nr	EURONORM	AISI-SAE
XC42TS	C43	-	-	-	-
XC48	C48	CK45	-	C46	1045
-	38Cr4	38Cr4	7043	38Cr4	-
-	36CrMn4	-	-	-	-
42CD4TS	41CrMo4	41CrMo4	7223	41CrMo4	(4140)
40NCD3TS	40NiCrMo3	-	-	40NiCrMo3	-

Aciers pour roulement

NF	UNI	DIN	W.Nr	EURONORM	AISI-SAE
100C6	100Cr6	100Cr6	3505	100Cr6	52100
-	100CrMn4	(100CrMn6)	(3520)	(100CrMn6)	-
100CD7	100CrMo7	W5	(3536)	(100CrMnMo7)	-

[http://www.direct-transmission.fr/docs/guides/Michaud_Chailly_Technique-correspondances-normes-aciers.pdf]

or https://mdmetric.com/tech/InternationalMaterialGradeComparisonTable.pdf

Outline

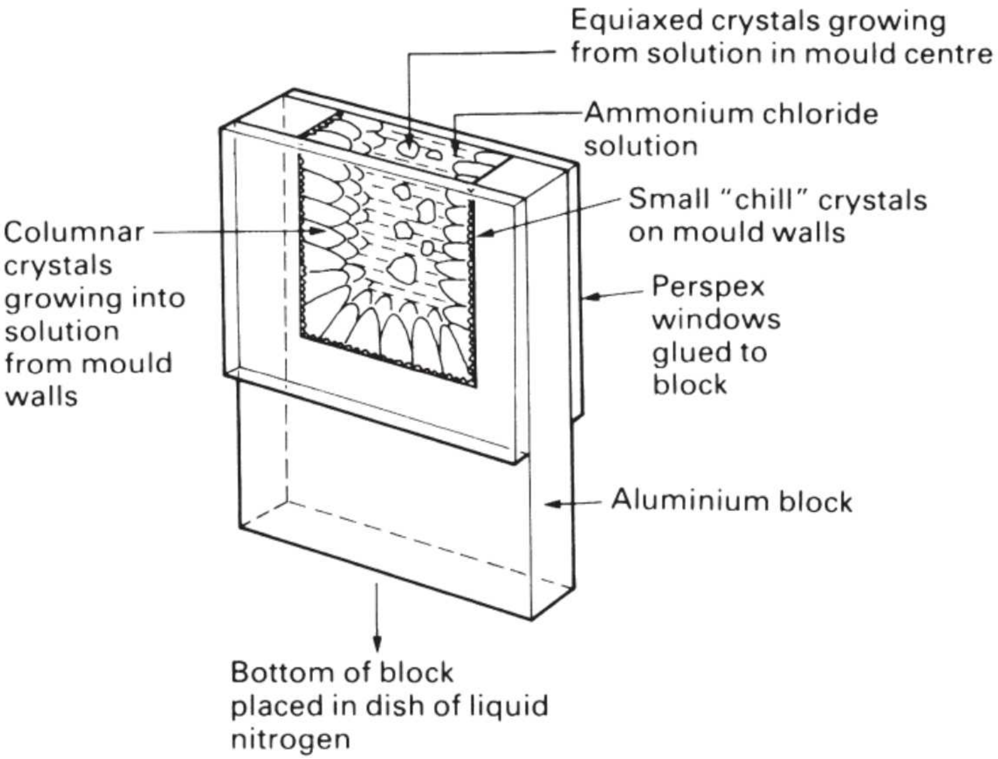
- Introduction
- Light alloys
- Carbon steels
- Alloy steels
- Production, forming and joining of metals
  - Ingot casting
  - Rolling
  - Welding
  - 3D printing...

Production, forming and joining of metals

Ingot casting, rolling, welding, 3D printing...

Ingot casting

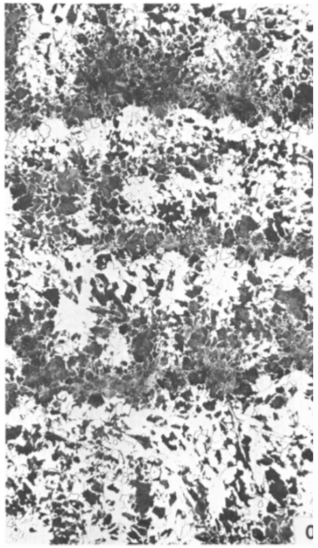
- Solidification structure?



[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

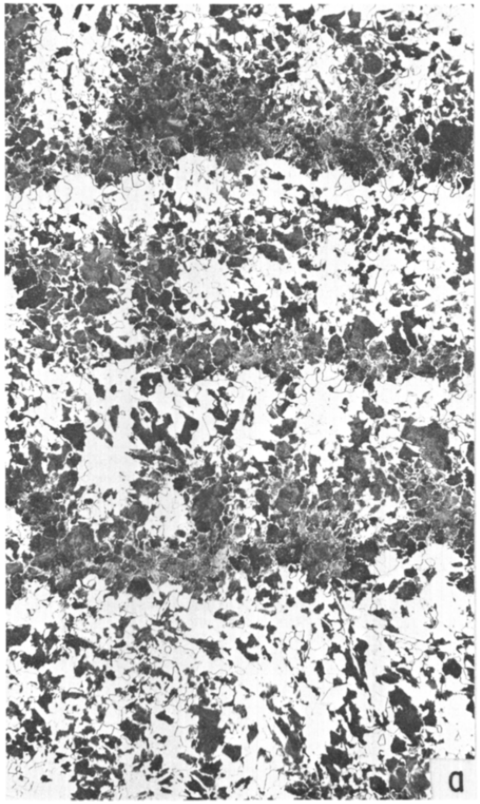
Impurities or alloying elements get "pushed" ahead of the solidification front

$\Rightarrow$ **Segregation**



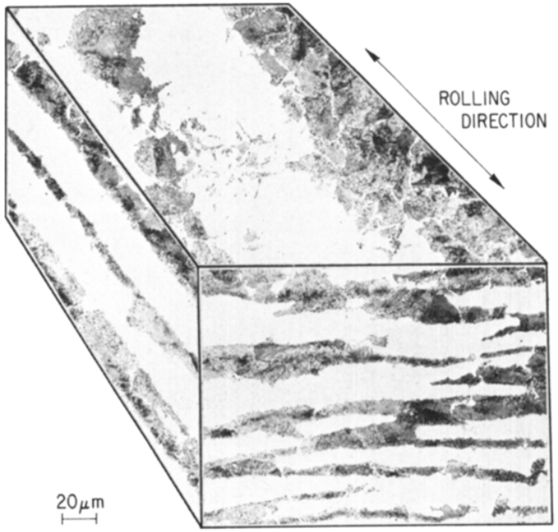
[Grange, Metall. Trans., 1971]

Ingot casting and banding

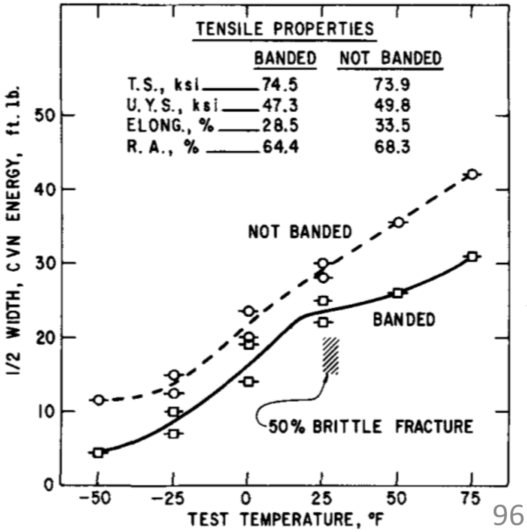


Ingot structure

After rolling



Toughness



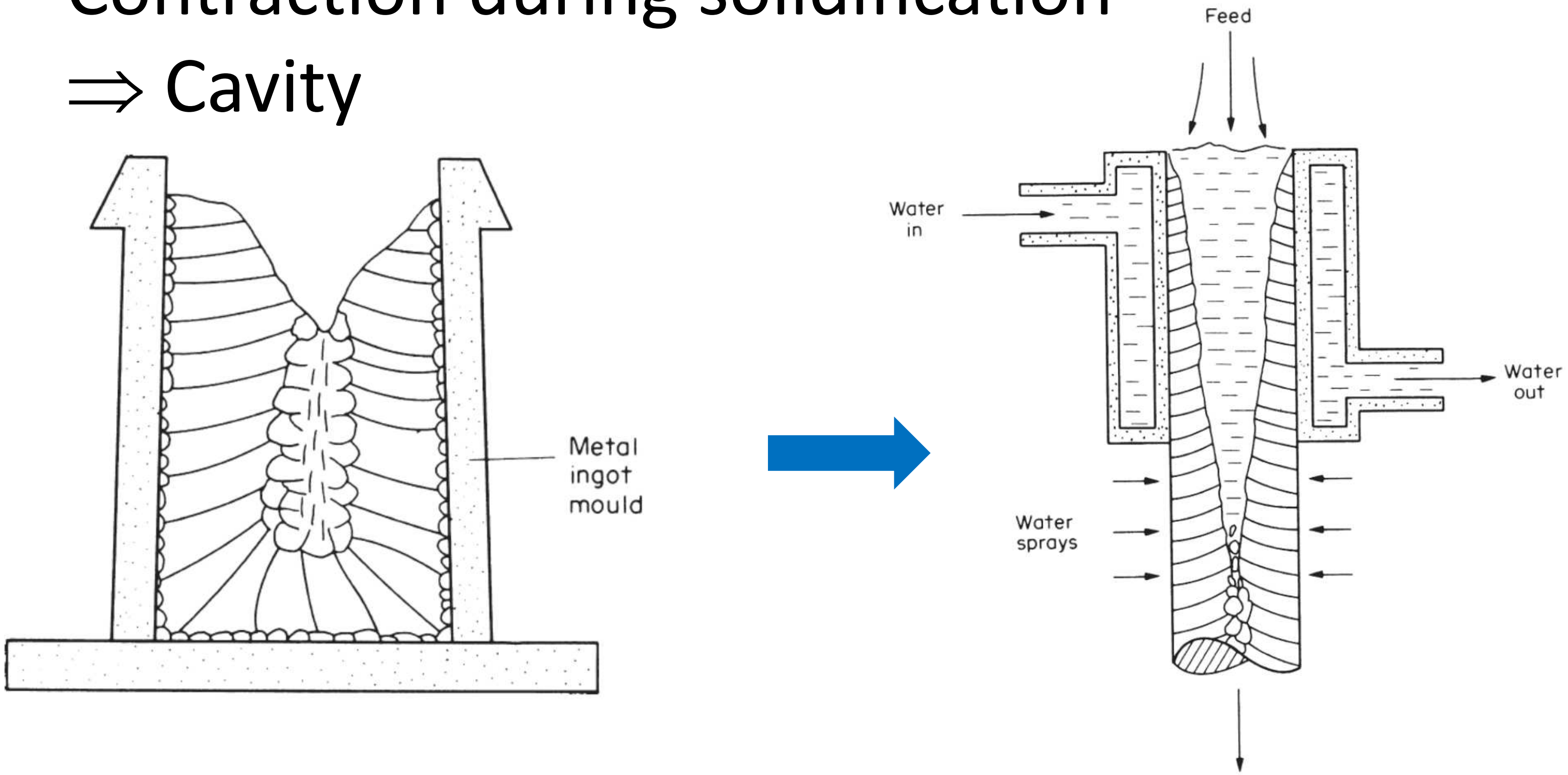
TENSILE PROPERTIES

	BANDED	NOT BANDED
T.S., ksi	74.5	73.9
U.Y.S., ksi	47.3	49.8
ELONG., %	28.5	33.5
R.A., %	64.4	68.3

[Grange, Metall. Trans., 1971]

Ingot vs continuous casting

- Contraction during solidification
  $\Rightarrow$ Cavity



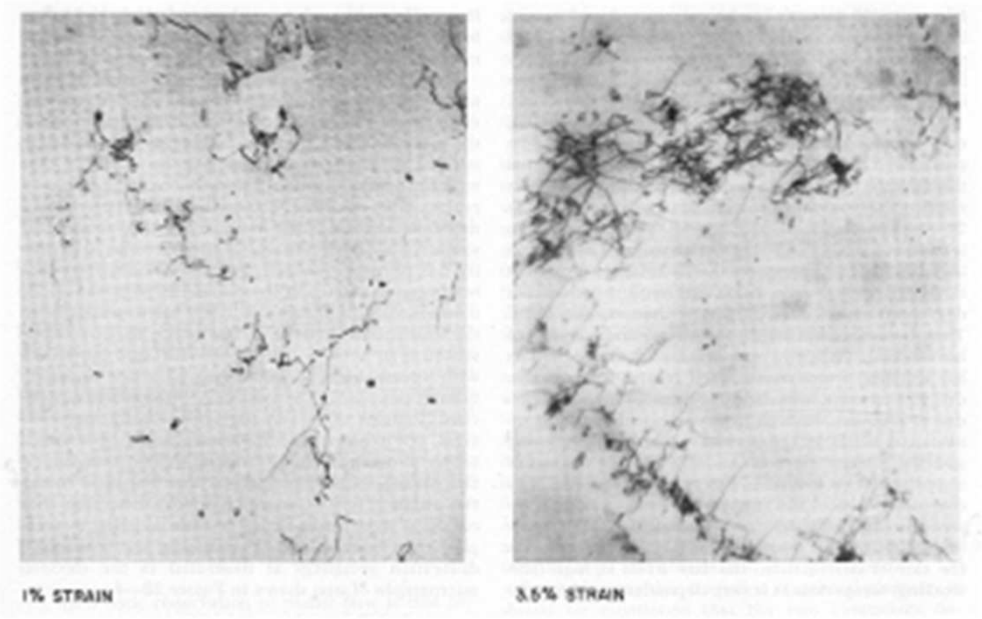
In continuous casting, liquid metal is fed continuously (no cavity) and columnar grains grow over smaller distance (segregation ↓)

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Rolling, recovery and recristallisation (1)

- Rolling relies on plastic deformation

⇒ Work hardening may become a problem



1% STRAIN

3.5% STRAIN

Dislocations density ↑

⇒ Entanglement

⇒ Dislocations glide more difficult

⇒ Strength ↑

⇒ **Work hardening**

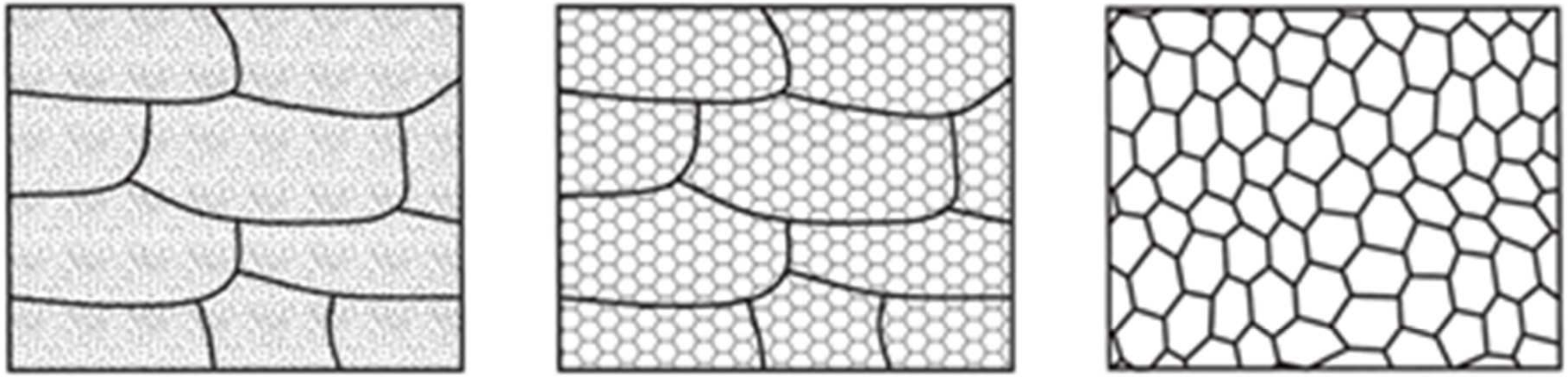
[J. Lecomte-Beckers, Phys0904 "Physique des Matériaux"]

Rolling, recovery and recristallization (2)

- Rolling relies on plastic deformation

$\Rightarrow$ Work hardening may become a problem

$\Rightarrow$ Annealing to favour recovery/recristallization



Deformed structure

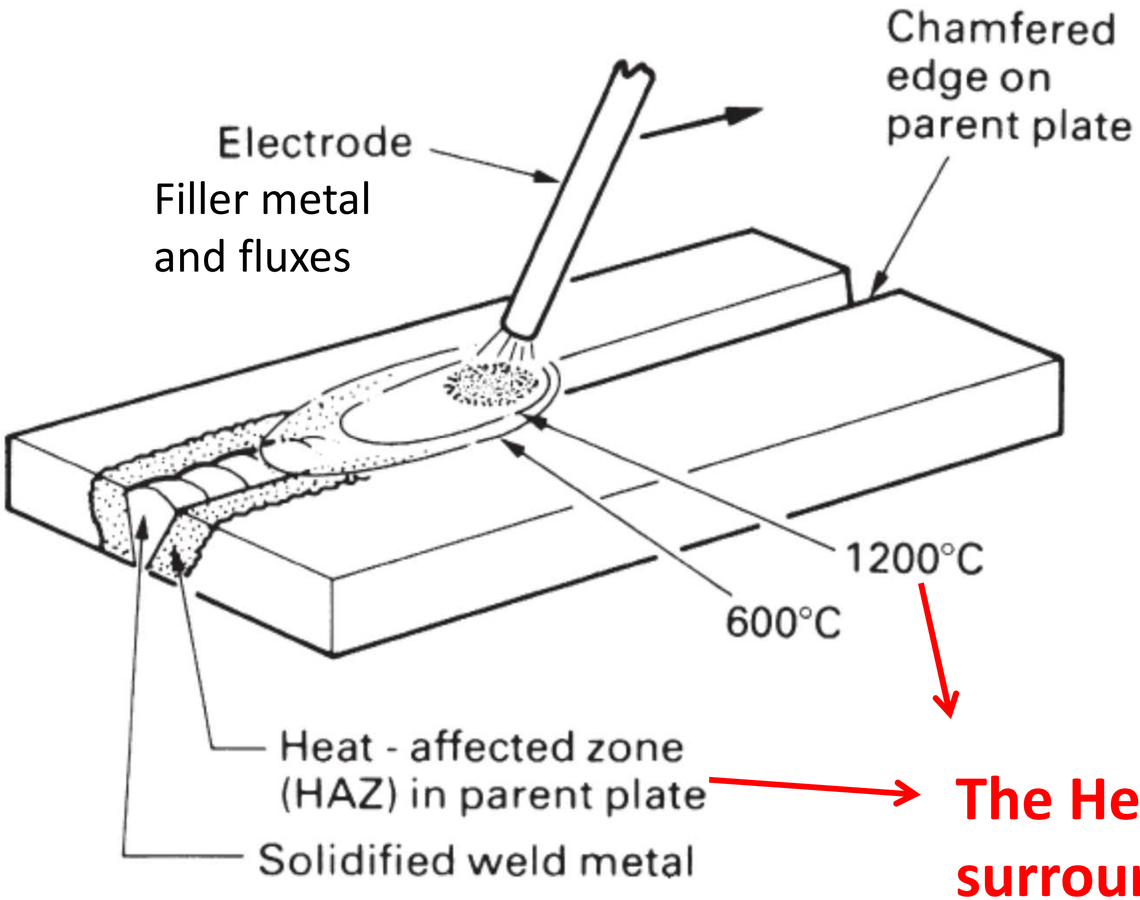
Recovery = organisation of crystalline defects

Recrystallization = formation of new grains

≠ structures ⇒ ≠ properties

[J. Lecomte-Beckers, Phys0904 "Physique des Matériaux"]

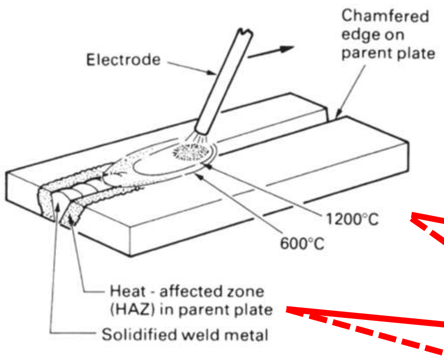
Welding steels (1)



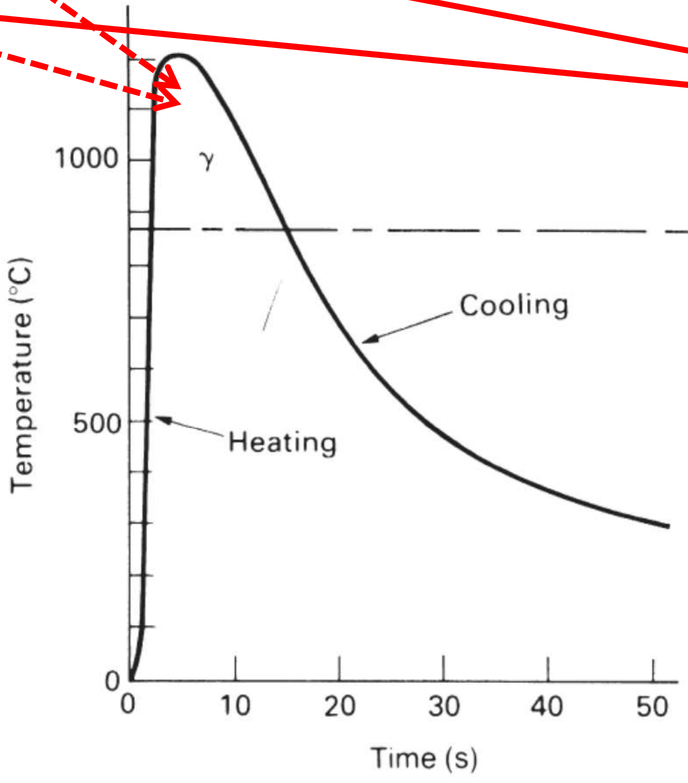
The Heat Affected Zone surrounding the weld is reheated in the austenitic phase field

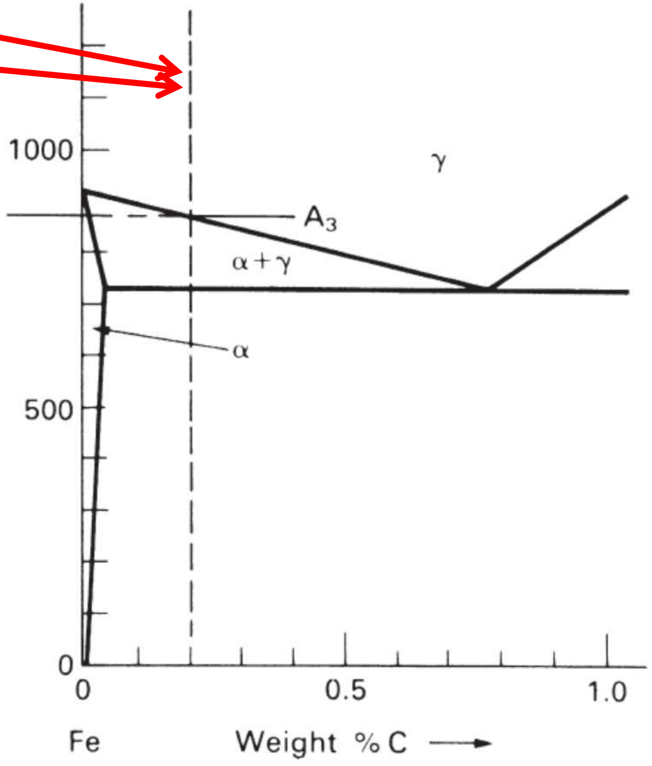
[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

Welding steels (2)



The Heat Affected Zone surrounding the weld is reheated in the austenitic phase field



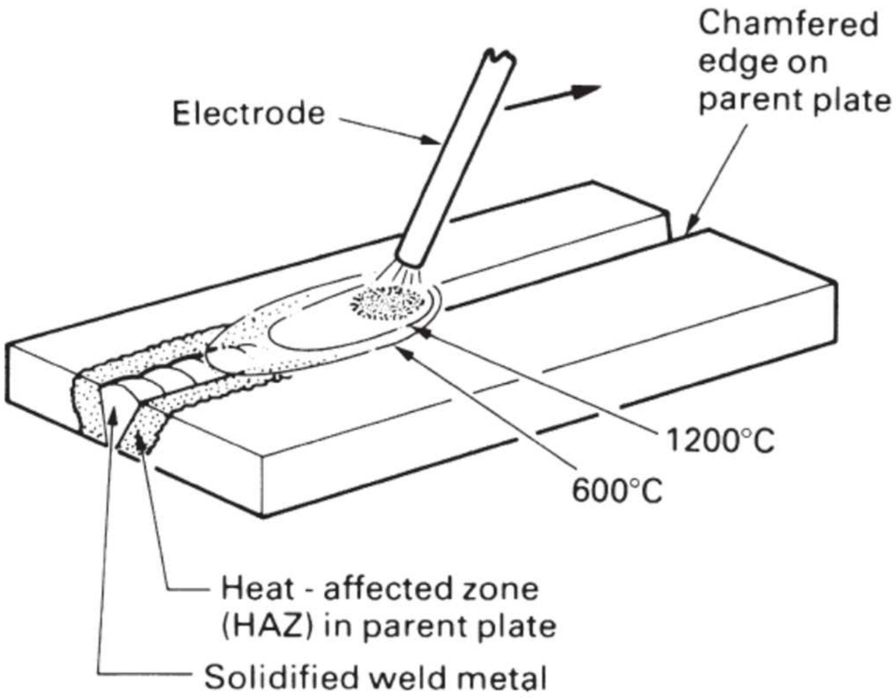


Rapid heating is followed by rapid cooling through conduction in the parent metal

⇒ Risk of forming martensite in the HAZ for C content > 0,5 wt%

[M.F. Ashby and D.R.H. Jones, Engineering Materials, vol. 2]

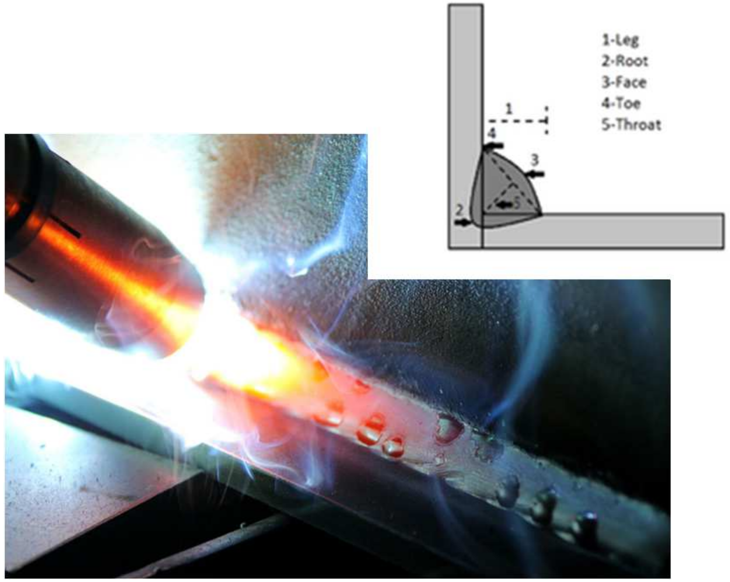
Welding steels (3)



Martensite is brittle in itself
+ it is prone to H_2 embrittlement

Fillet weld

Bigger heat sink
⇒ faster cooling
⇒ Risk of forming martensite ↑

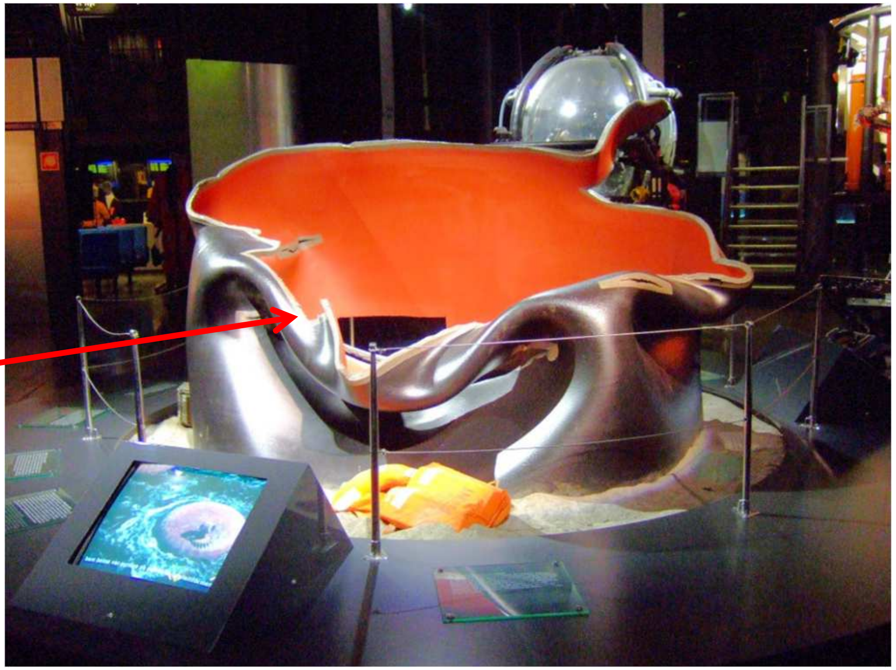


[By Dako99 - Own work, CC BY-SA 3.0]

Welding steels (4)

Collapse of the Alexander Kielland oil platform (March 1980)

[Norsk Oljemuseum - Norwegian Petroleum Museum]

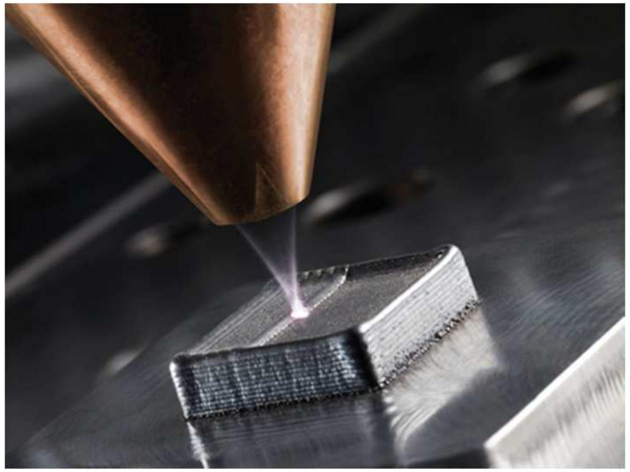


[By Jarvin - Own work, CC BY 2.5]

And this all started from a crack at a small fillet weld!

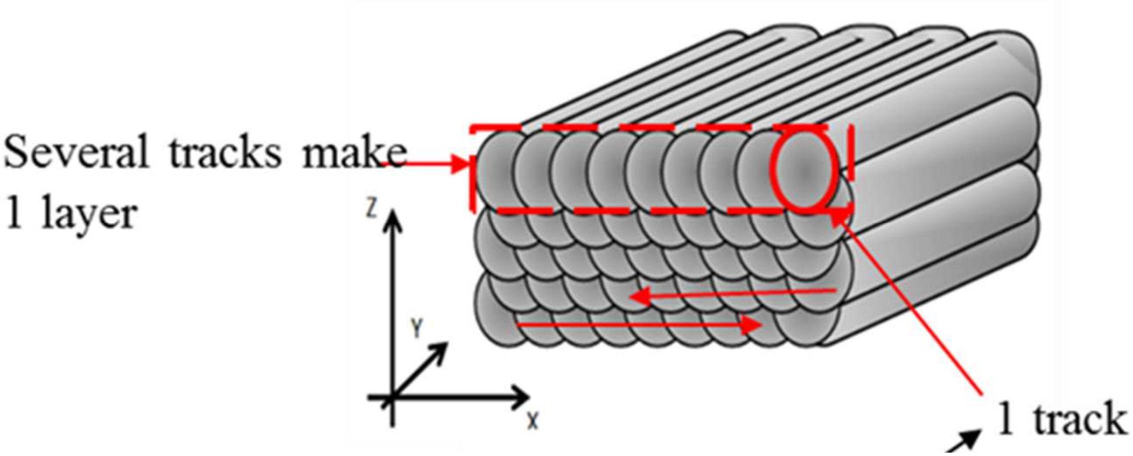
https://www.twi-global.com/news-events/case-studies/alexander-l-kielland-accommodation-platform-145/

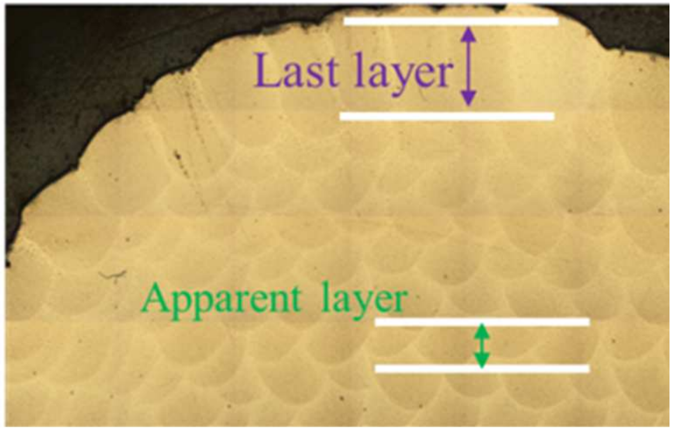
3D printing of metals (1)



A metallic powder is simultaneously deposited and melted using a laser beam

One track // one weld bead



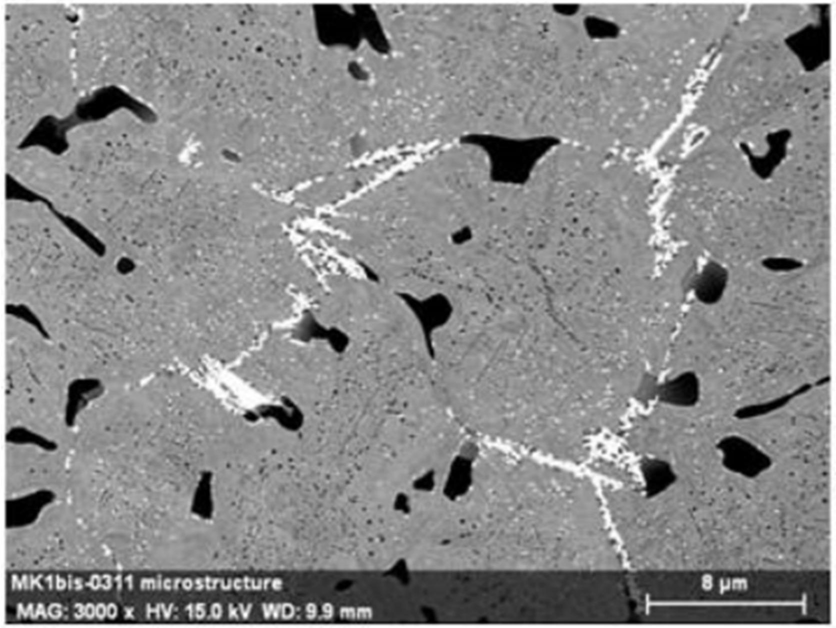


[N. Hashemi, ULg, 2017]

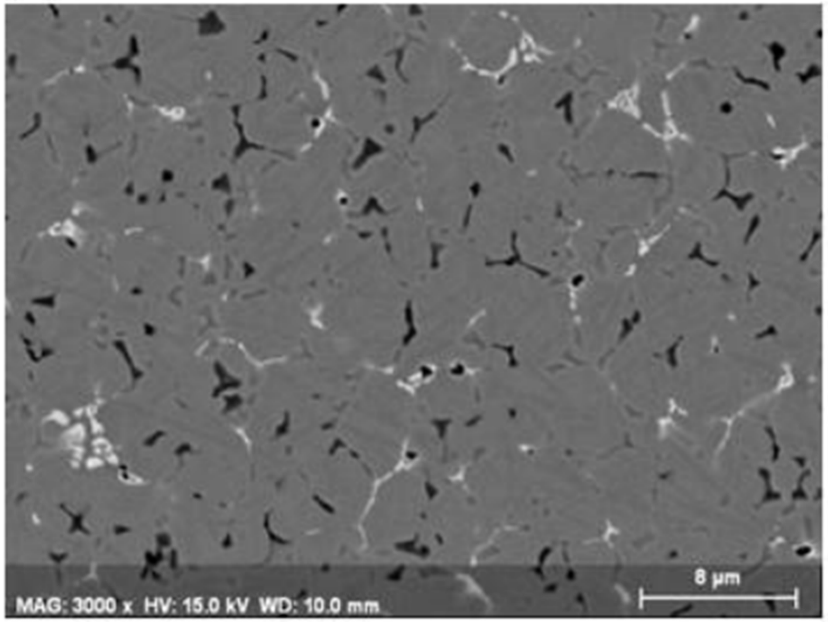
3D printing of metals (2)

High Speed Steels

- Cr, Mo, V, W to form hard carbides
- Fast cooling $\Rightarrow$ Finer structure



Conventional casting



3D printing

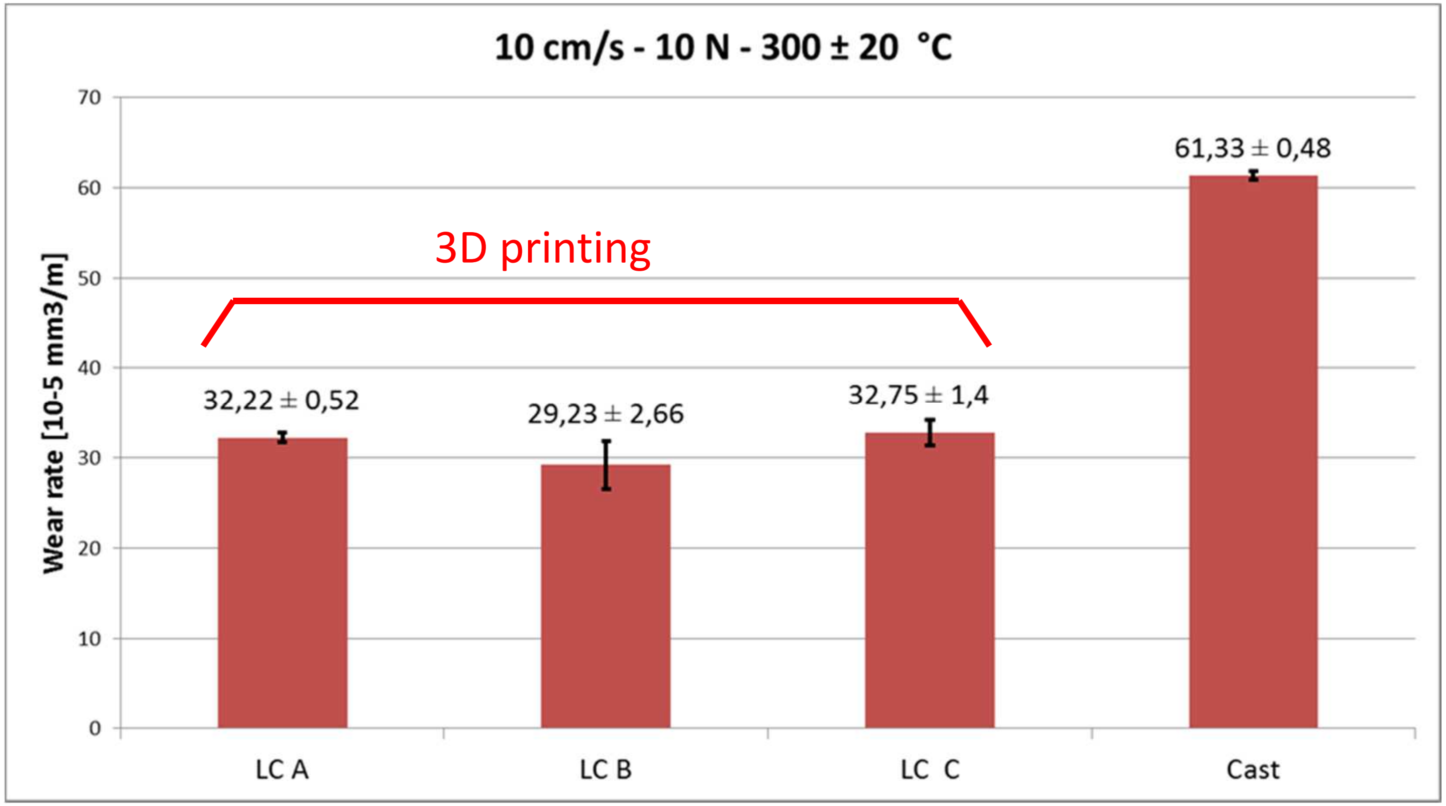
[N. Hashemi, ULg, 2017]

3D printing of metals (3)

High Speed Steels

- Cr, Mo, V, W to form hard carbides
- Fast cooling ⇒ Finer structure

  ⇒ Improved wear resistance



[N. Hashemi, ULg, 2017]

Summary

Materials selection: desired properties

⇒ Materials properties may be

- structure independent (E,c_p...)
- structure dependent (σ_y, fatigue resistance...)

⇒ Structure may be controlled by

- Chemical composition (equilibrium)
- All structural changes = **History** of the material

⬇

Production, forming and joining