Materials Lab
HSLU, Semester 3

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Contents

Exam

10 pages individual summary, printed/written on paper (pictures allowed). Calculator, ruler, electrochemical series.

Part I

Physical metallurgy

1 Material classes, structural models, basic concepts

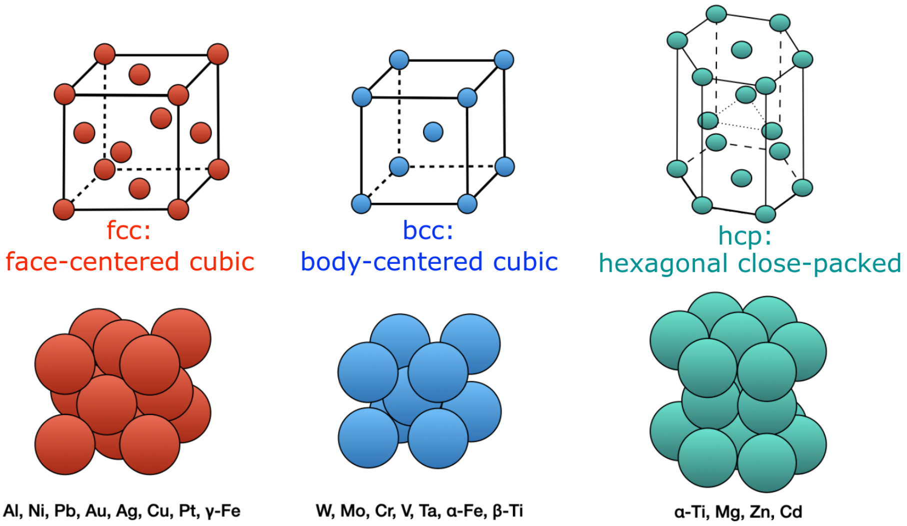
1.1 Material classes and typical properties

Class	4 Typical Properties
Metals / Alloys	1) Conductivity (electric, thermal) 2) Ductility / malleability 3) Castable 4) Shiny (reflective)
Ceramics	1) High temperature resistance (High E, Low α) 2) High compression strength 3) Insulator (electric, thermal) 4) Wear resistance
Polymers	1) Cheap 2) Insulating (electric, thermal) 3) Longevity (corrosion resistance) 4) Moldable

1.2 Structural model of metals

In general, metals have:

- **Metallic bonding**
- Good electrical and thermal conductivity
- Simple, densely packed crystal structures (atomic distances $\sim 0.1 - 0.2$ nm)



FCC (Face-centered cubic)

- Packing efficiency:
  $$\phi = \frac{\pi}{\sqrt{18}} \approx 74\%$$
- Has many slip systems (12)
- Closest packed direction

BCC (Body-centered cubic)

- Packing efficiency:
  $$\phi = \frac{\sqrt{3}\pi}{8} \approx 68\%$$
- Has many slip systems (6)
- Not closest packed direction
- Cottrell atmosphere

HCP (Hexagonal close-packed)

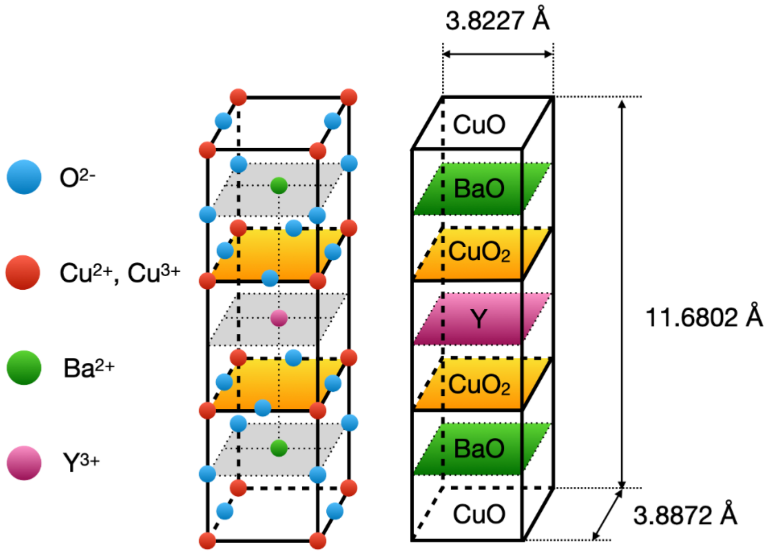
- Packing efficiency:
  $$\phi = \frac{\pi}{\sqrt{18}} \approx 74\%$$
- Very few slip systems (3)
- Closest packed direction

$$\boxed{\text{Packing efficiency } (\phi) = \frac{\text{Volume occupied by atoms in unit cell}}{\text{Total volume of unit cell}}}$$

1.3 Structural model of ceramics

In general, ceramics have:

- **Ionic bonding, complex crystal structures (ceramics), amorphous (glasses)**
- Undoped: insulators (doped: semiconductors, superconductors or ionic conductors)
- Brittle, but high chemical and thermal resistance
- Wear-resistant, other special properties (e.g. ferro-/piezoelectricity)

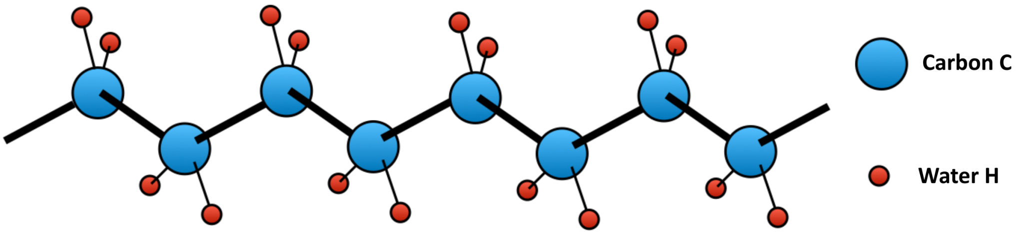


YBCO superconducting ceramic with layered perovskite-like structure

1.4 Structural model of polymers

In general, polymers have:

- Macromolecules (10^3 to 10^5 C atoms)
- **Weaker intermolecular bonds** (strong atomic bond in molecular chain)
- Electrically and thermally insulating (without special modifications)
- Cheap, moldable, massive waste problem (e.g. ocean pollution)
- Matrix for many composite materials (recycling problem)



Polymeric hydrocarbon chain

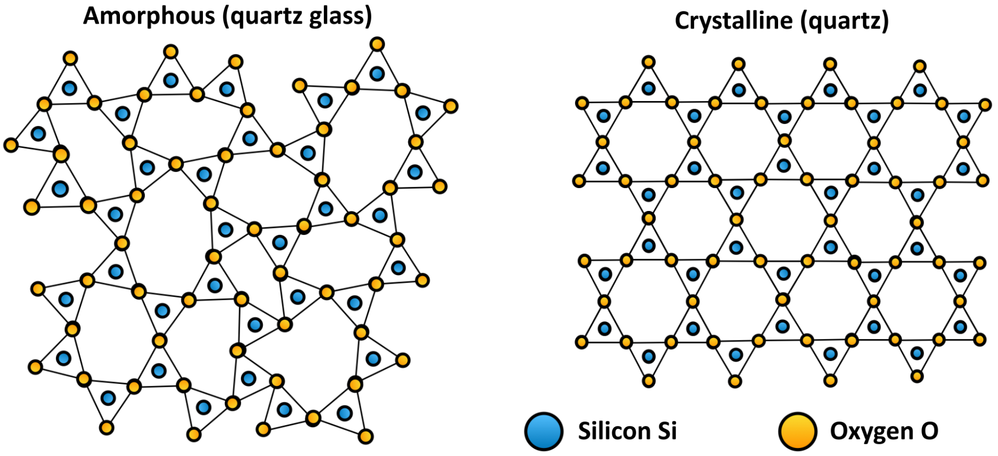
1.5 Amorphous and crystalline materials

Amorphous materials

- No crystal lattice (e.g. quartz glass, polymers)
- Atomic distances defined by chemical bonds
- Bond angles are variable

Crystalline materials

- Crystal lattice (e.g. metals, ceramics, quartz)
- Atomic distances and bonding angles are defined



1.5.1 Polycrystalline materials

Most metal components are polycrystalline (made of many grains/crystals), i.e. they consist of countless microscopic crystals (crystallites, “grains”).

1.5.2 Monocrystalline materials

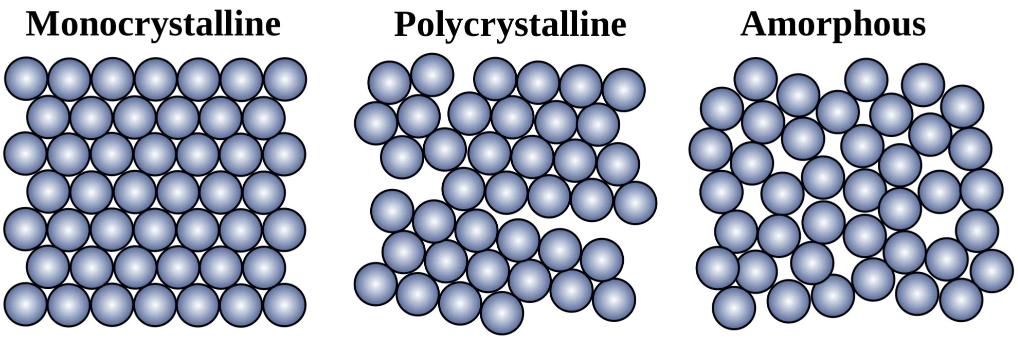
Only for special applications, expensive

- Single-crystal turbine blades ($T > 1000°C$, creep-resistant)
- Semiconductors, MEMS components made of silicon (e.g. gyroscopes in smartphones, accelerometers)
- Optical elements (e.g. laser crystals, $\lambda/4$ plates, crystals for frequency doubling of lasers)

1.5.3 Amorphous materials

- Inorganic glasses (also Gorilla glass of smartphones)
- Metallic glasses (ferrous transformer sheet metal)
- Amorphous plastics (e.g. PMMA - plexiglass, COC, . . .)

1.5.4 Structure difference



1.6 Directionals dependence of the properties of materials

1.6.1 Anisotropy and Isotropy

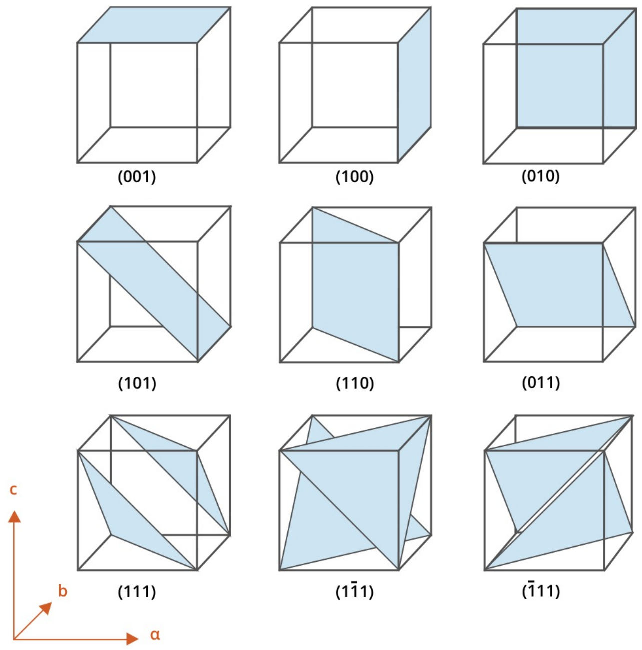
- Anisotropic: Properties depend on direction (e.g. single crystals, wood, composites)
- Isotropic: Properties do not depend on direction (e.g. polycrystalline metals, amorphous materials)

1.6.2 Anisotropy of the Young’s Modulus E in most cubic crystals

In most cases, the E is the largest in the direction of the closest packed atomic planes, in direction of the space diagonal $\langle 111 \rangle$.

1.6.3 Miller indices for crystal directions

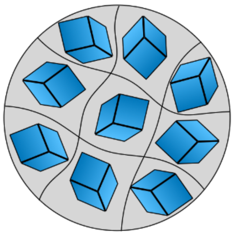
In short, the Miller indices are the reciprocals of the fractional intercepts that the plane makes with the crystallographic axes:



1.7 Directional dependence of properties in polycrystalline materials

1.7.1 Polycrystalline materials without texture

The polycrystalline materials without texture are considered **quasi-isotropic**, because the grains are randomly oriented.

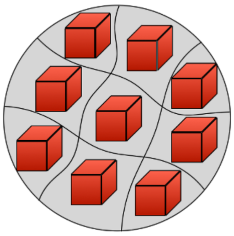


Polycrystalline material without texture

Notice: each crystal is anisotropic. but the material is quasi-isotropic to the outside, directional dependence "averages out"

1.7.2 Polycrystalline materials with texture

The polycrystalline materials with texture are considered **anisotropic**, because the grains are preferentially oriented.



Polycrystalline material with texture

1.8 Material properties wrap-up

1.8.1 Single crystal materials

- **Anisotropic**
- Properties depend on direction
- Not uniform = anisotropic

1.8.2 Polycrystalline materials without texture

- **Quasi-isotropic**
- Each crystal: anisotropic
- Uniform properties in all directions: isotropic → quasi-isotropic

1.8.3 Polycrystalline materials with texture

- **Anisotropic**
- Preferential orientation of the crystallites: texture → anisotropic
- Examples: rolled and recrystallized electrical sheets with Goss texture

1.8.4 Amorphous materials

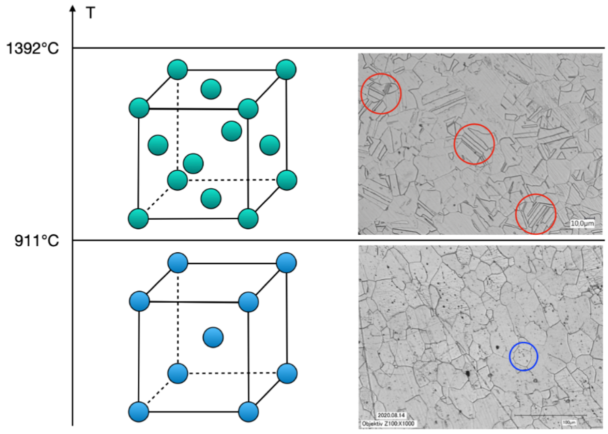
- **Isotropic** (e.g. glass or amorphous metals)

1.9 Polymorphism (Allotropy)

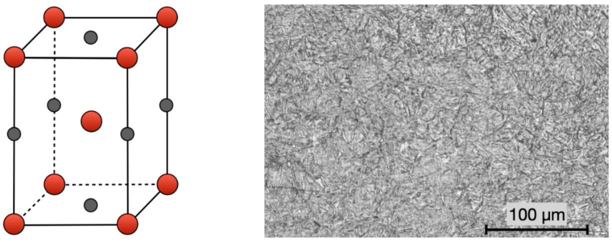
Some materials may exhibit more than one crystal structure:

- Iron $\begin{cases} \alpha\text{-Fe (ferrite, BCC)} & \text{below } 911°\text{C} \\ \gamma\text{-Fe (austenite, FCC)} & 911°\text{C to } 1392°\text{C} \\ \delta\text{-Fe (ferrite, BCC)} & 1392°\text{C to } 1536°\text{C} \end{cases}$
- Titanium $\begin{cases} \text{HCP} & \text{below } 880°\text{C} \\ \text{BCC} & \text{above } 880°\text{C} \end{cases}$
- Shape memory alloys (e.g. NiTi)
- Carbon (graphite, diamond, graphene, fullerene, CNT, ...)
- Zirconia (high crack resistance due to phase transformation toughening)
- Ferro- and piezoelectric materials (e.g. PZT, quartz, ...)

1.9.1 Polymorphism of Iron (Fe)

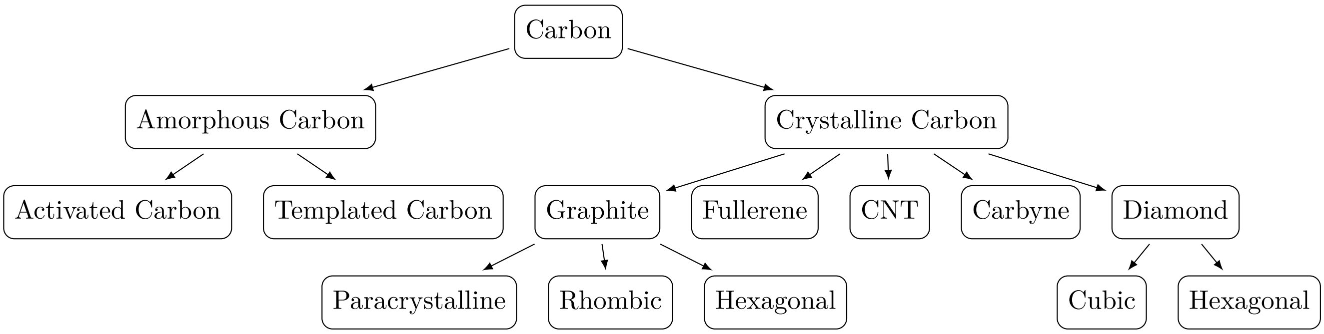


Slow Austenite transformation in steel: Ferrite



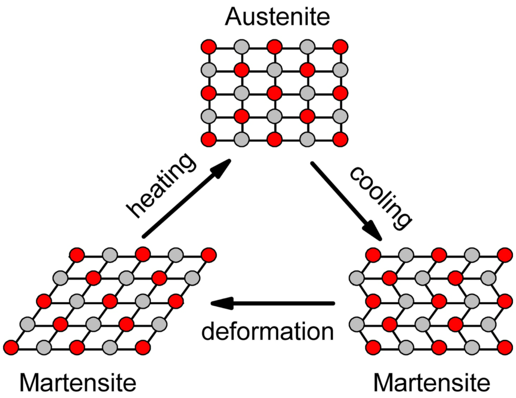
Fast Austenite transformation: Martensite

1.9.2 Polymorphism of Carbon (C)



1.9.3 Polymorphism of Nitinol (NiTi)

NiTi is a shape memory alloy (SMA), used for screen lock of tablet notebooks, medtech, and spectacle frames.



1.10 Microstructure and Phases

Phases are **homogeneous** subsections of a material with uniform physical and chemical properties:

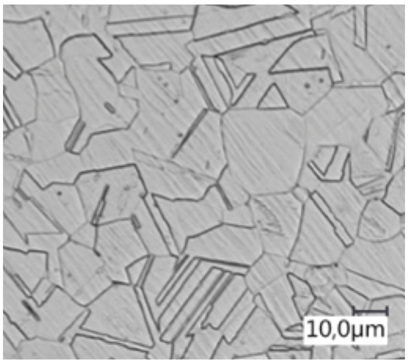
- A phase can be crystalline or amorphous
- At the phase boundaries, a sudden change in structure, properties and chemical composition occurs

Polycristalline materials can consist of:

- One phase (homogeneous microstructure, e.g. only iron crystals)
- Different phases (heterogeneous microstructure, e.g. graphite and iron)

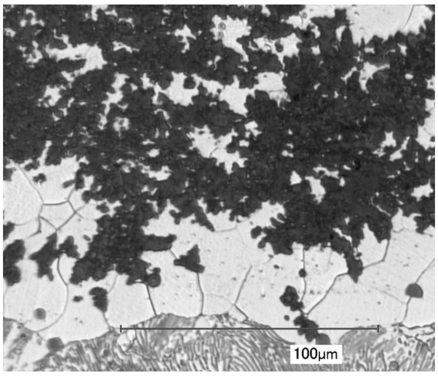
1.10.1 Homogeneous microstructure

They have only one phase and crystal structure:



1.10.2 Heterogeneous microstructure

They have multiple phases and many types of crystal structures:



1.11 Alloys

1.11.1 Definition of an alloy

An alloy is a metallic material of at least 2 types of atoms:

- Metal + Metal (iron-nickel, gold-silver, tin-lead, aluminum-copper, . . .)
- Metal + Non-metal (iron-carbon (steel), nickel-phosphorus, . . .)

1.11.2 Microstructure of alloys

- **Homogeneous**, single-phase, only one type of cristal: SOLID SOLUTION CRYSTAL
- **Heterogeneous**, multi-phase, MIX OF DIFFERENT CRYSTAL TYPES:
  - Crystals of pure metals without impurity atoms (no solid solution crystals)
  - Solid solution crystals with impurity atoms,
  - Crystals of intermetallic or intermediate phases (chem compounds crystals with their own distinguished crystal structure e.g. Ni_3Ti, Fe_3C, . . .)
  - (Impurity particles, e.g. added ceramic particles or slag residues)

2 Most important metal structures and crystal lattice defects

2.1 Lattice defects

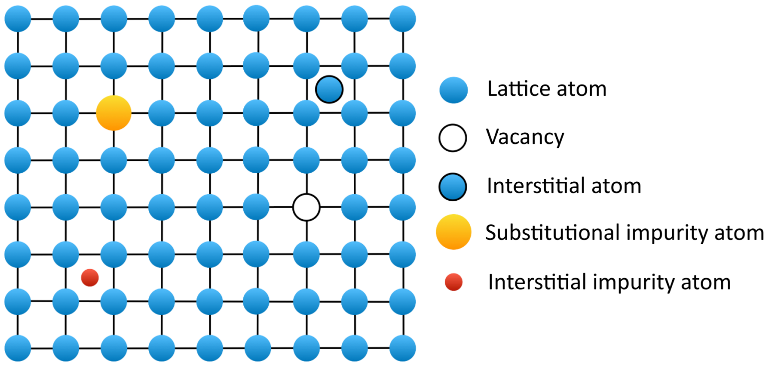
Lattice defects are irregularities in the crystal structure:

- **0-dimensional defects** (point defects)
- **1-dimensional defects** (line defects)
- **2-dimensional defects** (surface defects)
- **3-dimensional defects** (volume defects)

2.1.1 0-dimensional defect

0-dimensional defects include vacancies (missing atoms) and impurity atoms (foreign atoms in the lattice).

The approximate atomic size is 0.1nm.

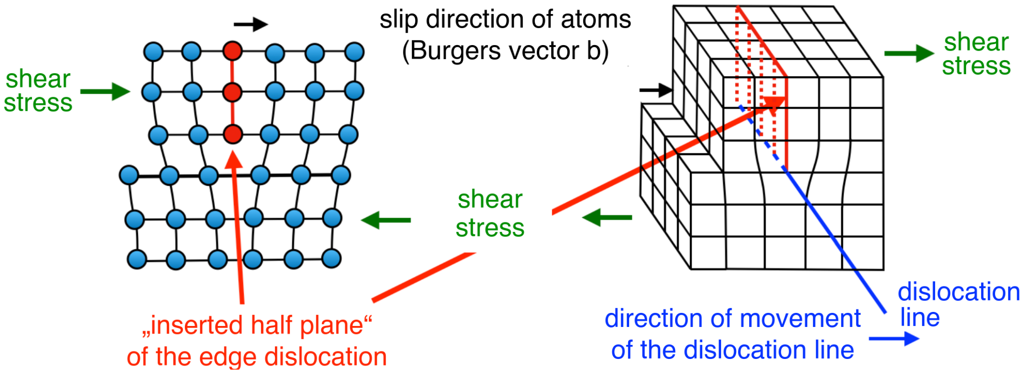


Point defects: vacancy, interstitial atom, substitutional atom

2.1.2 1-dimensional defect

1-dimensional defects are dislocations (line defects) in the crystal structure.

Edge dislocations insert an extra half-plane of atoms in the crystal, distorting the nearby planes of atoms.



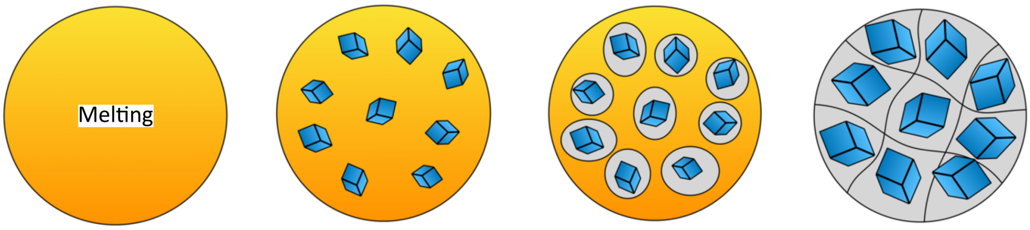
Line defects: edge dislocation, screw dislocation

2.1.3 2-dimensional defect

2-dimensional defects are grain boundaries (surface defects) in polycrystalline materials:

- Crystal growth starts at multiple locations within the molten metal.
- Finally, the growing grains merge to form the microstructure of the solid metal.

The approximate atomic size is 10 to 100 μm.

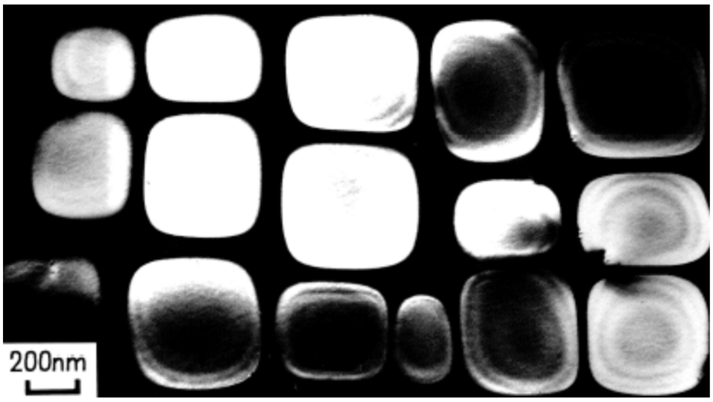


Crystallization from a melt:
(1) homogeneous melt, (2) nucleation of crystals, (3) crystal growth surrounded by residual melt, (4) fully solidified polycrystalline structure with grain boundaries

2.1.4 3-dimensional defect

3-dimensional defects are precipitates, inclusions, voids, cracks (volume defects) in the crystal structure.

The size is very small (nanometers)



Coherent Ni_3Al precipitates (white) in a Ni solid solution crystal (black)

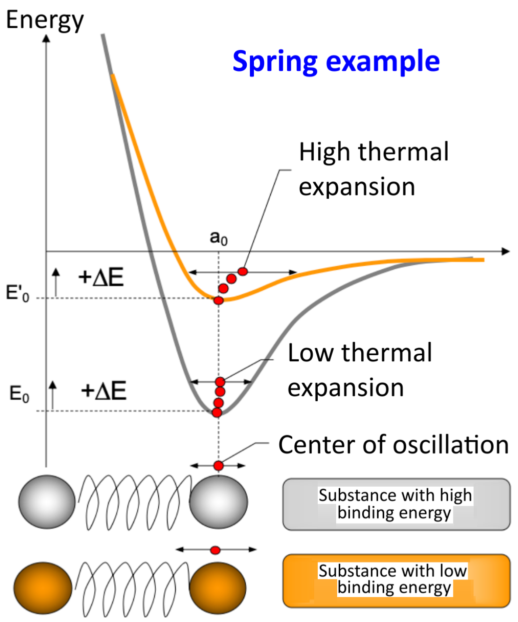
3 Elastic and plastic deformation

3.1 Elastic deformation

3.1.1 Atomic energy-distance model

The atomic energy-distance model describes the interaction between two atoms.
The coefficient of thermal expansion α is inversely proportional to:

- Young's modulus E (in case of springs, the force)
- Bonding energy
- Melting temperature



3.2 Elastic constants of isotropic materials

3.2.1 Elastic stress, strain, and Young's modulus

Letting the load be unidirectional and in x-direction, then:

$$\boxed{\varepsilon_x = \frac{1}{E} \cdot \sigma_x \iff \sigma_x = E \cdot \varepsilon_x}$$

3.2.2 Poisson's ratio ν

When a material is stretched in one direction (x-direction), it tends to contract in the other two directions (y- and z-directions).

The ratio of the transverse strain to the axial strain is called Poisson's ratio:

$$\boxed{\nu = -\frac{\varepsilon_y}{\varepsilon_x} = -\frac{\varepsilon_z}{\varepsilon_x}}$$

3.2.3 Relationship between the 3 isotropic elastic constants G

For isotropic materials, the following relationships hold:

$$\boxed{G = \frac{E}{2(1+\nu)} = \frac{\sigma_x}{2\varepsilon_x(1+\nu)}}$$

3.3 Plastic deformation in metals

The plastic deformation has as characteristics to be permanent and non-reversible.

3.3.1 At room temperature

- Dislocations move on densely packed slip planes in densely packed directions
- Smaller slip distances require less external force or energy

Note: There are exceptions. For example, metals with relatively low stacking fault energy show:

- Twin formation (e.g. nitinol)
- Partial dislocations pairs with stacking faults in between (e.g. Ni, Cu)

3.3.2 At high temperatures

The metal creeps, leading to diffusion of atoms, especially at grain boundaries.

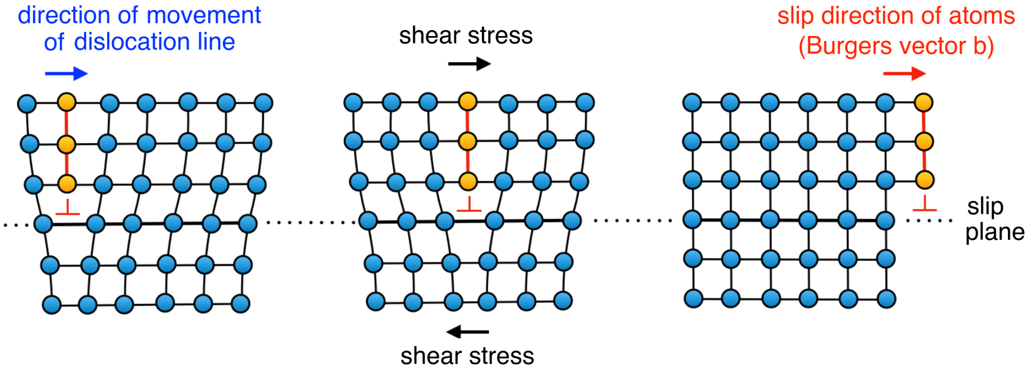
3.4 Dislocation Slip Model

The dislocation slip model describes the plastic deformation of metals by dislocation motion.

3.4.1 Simplified model

The simplified dislocation slip model is sufficient for practical understanding of plastic deformation:

- Inserted half-plane, the end of which forms the dislocation line
- Dislocation moves on densely packed slip planes

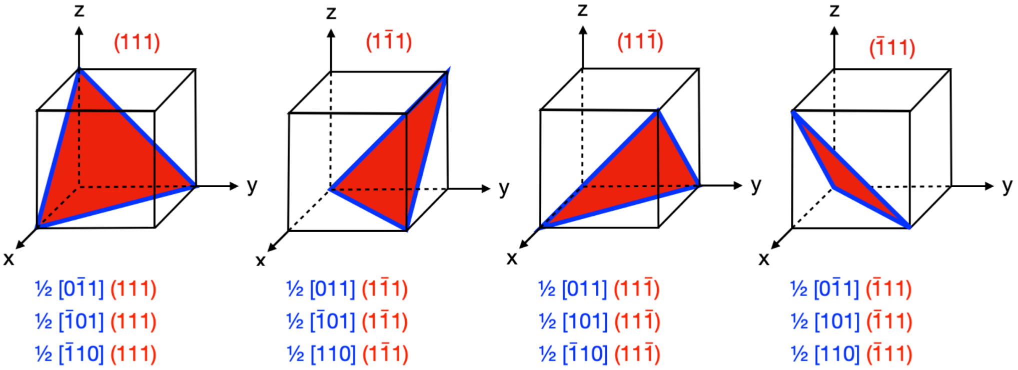


Edge dislocation motion under shear stress

3.5 Slip systems

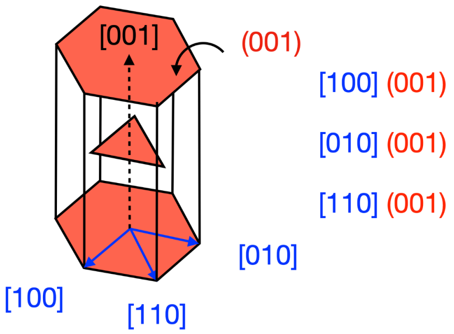
3.5.1 Slip systems in FCC metals (Miller indices)

FCC metals have 12 close-packed slip systems, making them soft and highly ductile (e.g. Au, Ag, Cu, Al, α-Fe)



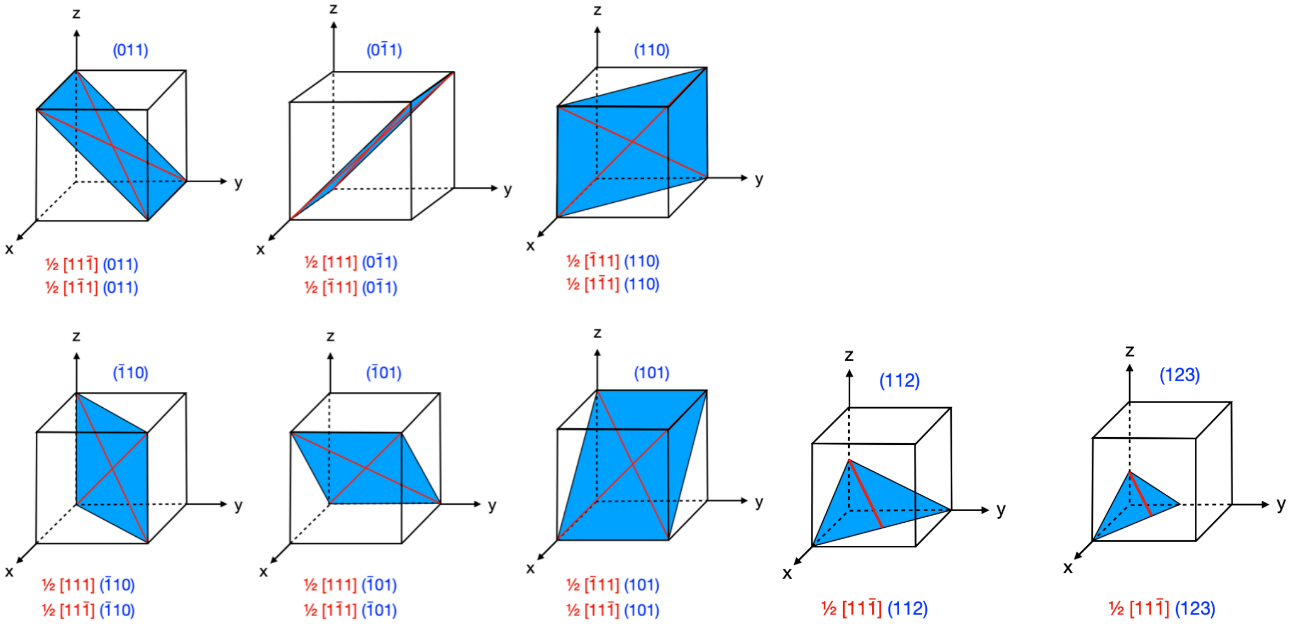
3.5.2 Slip systems in HCP metals (Miller indices)

HCP metals are closely packed but deform on only one slip plane with 3 slip systems, resulting in limited ductility (e.g. Ti, Zn, Mg).



3.5.3 Slip systems in BCC metals (Miller indices)

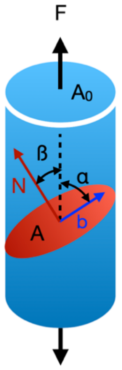
BCC metals have 48 slip systems but are less closely packed, leading to higher strength and lower ductility (e.g. α-Fe, Cr, W, Mo, Ta, Nb)



12 major slip systems: 6 $\{110\}$ slip planes
2 slip directions: $1/2\langle 111\rangle$ each

36 minor slip systems:
12x $1/2\langle 111\rangle\ \{112\}$
24x $1/2\langle 111\rangle\ \{123\}$

3.6 Schmid's law of critical resolved shear stress



The Schmid's law states that slip begins in a crystalline material when the resolved shear stress on a slip system reaches a critical value.

- PLastic deformation occurs only on closely packed slip planes where the applied shear stress exceeds a critical value
- Under uniaxial loading, the maximum shear stress acts on slip planes inclined at 45° to the load axis

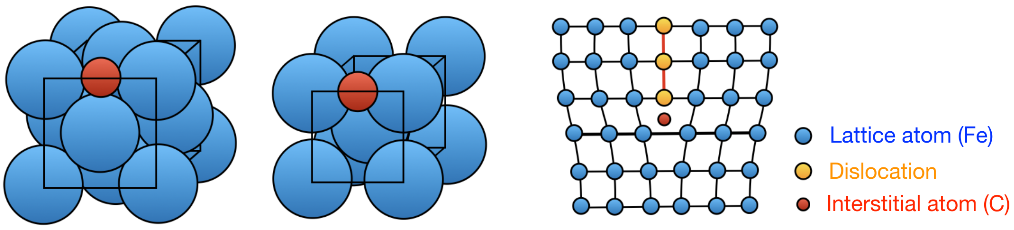
3.7 Correlation between metals crystal structure and ductility

Metal	**Ductility**	**Packing structure**	**Slip systems**	**Slip system orientation**
FCC	Highest ductility among metals	Closest-packed (74%)	4 slip planes → 12 slip systems	Very high probability of favorable orientation (Schmid's law)
BCC	Lower ductility than FCC, but still generally good	Less closely packed (68%)	Many slip planes and slip systems	Strength often higher than FCC metals
HCP	Limited ductility under normal conditions	Closest-packed (74%)	Only 1 slip plane → 3 slip systems	Low probability of favorable orientation (−45° to load axis)

3.8 Particulatiries in BCC metals

3.8.1 Cottrell atmospheres and Dislocation pinning

- In $\alpha-$iron with a BCC structure (ferrite), the octahedral sites for interstitial atoms such as carbon or nitrogen are much smaller than in $\gamma-$iron with an FCC structure (austenite)
- As a result, carbon atoms in ferrite preferentially diffuse into the distortion fields near dislocation lines, where more space is available, forming so-called **Cottrell atmospheres**
- These atmospheres are responsible for the pronounced upper yield point (R_{eH}) observed in tensile tests of many BCC metals, as well as for the brittle fracture behavior at low temperature in impact tests
- During plastic deformation, dislocations must first break free from the Cottrell atmosphere. This process is especially difficult at low temperatures or high strain rates, leading to strong dislocation pinning



Carbon atoms occupy small octahedral sites (left), preferentially diffuse to dislocation regions (center), which forms Cottrell atmospheres that pin dislocations (right)

4 Strengthening mechanisms

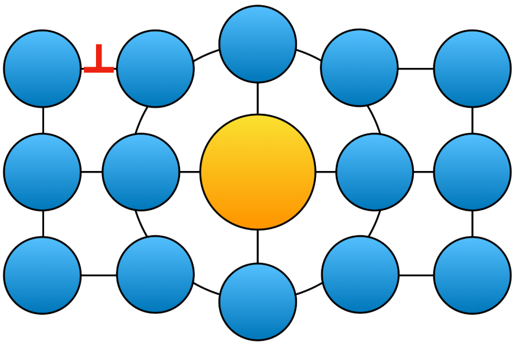
4.0.1 Metals mechanisms

Lattice defects act as deliberate obstacles that impede the motion of dislocations.

Dim	**Lattice Defect**	**Strengthening Mechanism**	**Increase in 0.2% Yield Strength**
0-D	**Substitution / Interstitial atoms** with concentration of c in the solid solution crystal	Solid solution hardening	$\Delta R_{p0.2} \sim c^{1/2}$
1-D	**Dislocations** (dislocation density N)	Strain (cold-work) hardening	$\Delta R_{p0.2} \sim N^{1/2}$
2-D	**Grain boundaries** defining an average grain size of d	Grain boundary hardening strength and ductility still good	$\Delta R_{p0.2} \sim d^{-1/2}$
3-D	Coherent **precepitates** with a size of D (also: semi-coherent and incoherent precipitates and dispersion particles)	Precipitation hardening	$\Delta R_{p0.2} \sim D^{1/2}$

4.0.2 0-dimensional: Solid-solution hardening

- Impurity atoms in a solid solution create lattice distortion fields that impede dislocation motion
- Interstitial atmos cause stronger lattice distortions than substitutional atoms, leading to a greater strengthening effect
- A larger atomic radius mismatch and higher impurity concentration both increase the strengthening effect
- **Result**: increased strength but reduced ductility



Edge dislocation in a crystal lattice with a substitutional impurity atom

SSH application fields:

- Al-Mn and Al-Mg alloys (5000 and 3000) for:
    - Automotive sheet metal
    - Airplane outer skin
    - Beverage cans
    - Sandwich honeycomb structures in lightweight structures
- Structural and stainless steels
- Gold jewerly (Au with Ag, Cu, Ni, Pt, Pd, . . .)

5 TODO

Part II

Strength and Ductility

6 Properties of material

Property	**Context**	**Characteristic values**
Mechanical	Withstanding static or dynamic loads/forces/stress	Young's modulus, static strength, hardness, fatigue strength, creep strength, toughness, ductility
Technological	Material processing	Formability, welding suitability, castability, hardenability
Physical	Various functional properties	Electrical and thermal conductivity, transparency, magnetizability, refraction index, . . .
Chemical	Resistance to normal or harsh environments	Resistance against corrsion, UV light or oxidizing agents, food safety, biocompatibility, toxicity

6.1 Failure hypotesis and Material testing methods (examples)

Failure hypothesis	**Material testing methods**
Failure of metals due the plastic deformation (dislocation slip) under static stress	Tensile test, compression test, bending test, torsion test
Failure due the crack formation and crack growth under dynamic oscillating stress	Fatigue tests (HCG, LCF)
Failure due the crack growth under sudden impact (crack growth under constant load)	Impact notch toughness test (Fractures mechanics)
Failure due the plastic deformation at high temperatures (diffusion, especially along the grain boundaries) under static stress	Creep test (or relaxation test)

7 Tensile test

7.1 Engineering Stress and Stress conditions

7.1.1 Engineering stress σ

Engineering stress is the force F acting on the original cross-sectional area S_0:

$$\boxed{\sigma = \frac{F}{S_0}}$$

7.1.2 Normal stress

The normal stress, similar to σ, is the force F_N that acts perpendicularly to S_0:

$$\boxed{\sigma = \frac{F_N}{S_0}}$$

7.1.3 Shear stress

Shear stress is the force F_Q parallel to the original surface S_0:

$$\boxed{\tau = \frac{F_Q}{S_0}}$$

7.1.4 Engineering strain ε

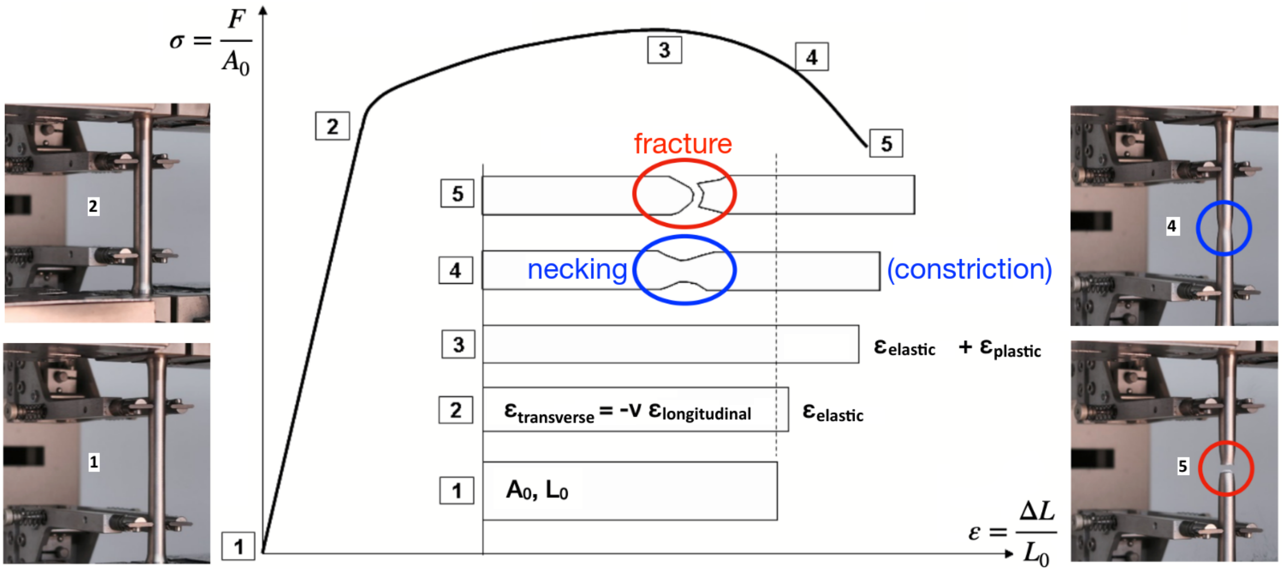
Engineering strain is the ratio of the change in length to the original length of a material under load:

$$\boxed{\varepsilon = \frac{\Delta L}{L_0} = \frac{L_1 - L_0}{L_0}}$$

7.1.5 Hooke's law

Within the elastic limit of a material, the deformation (strain) is directly proportional to the applied stress:

$$\boxed{\sigma = E \cdot \varepsilon}$$



Tensile test with of a BCC metal without the upper yield point R_{eH}

7.2 Elastic characteristics of some metals

Metal	Poisson's ratio ν	Young's modulus E [N/mm^2]	Shear modulus G [N/mm^2]
Mg	0.28	44'300	17'200
Al	0.34	70'600	26'500
Ti	0.36	111'800	40'200
$\alpha-$Fe	0.25	206'000	82'400
Steel	0.28	206'000	80'440
Cu	0.35	122'530	45'130
Brass	0.41	103'000	36'490
Zn	0.25	130'010	41'200

7.3 Typical stress-strain behavior of metals

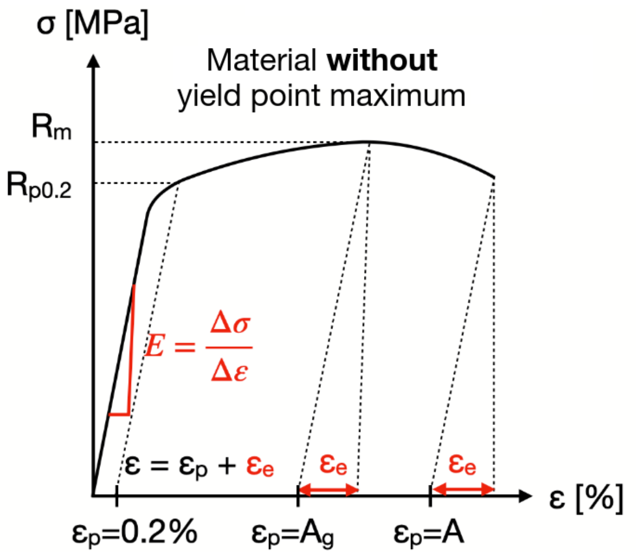
If the applied force is too big:

- Starting of Dislocation slip
- Plastic deformation

7.3.1 Yield Strength

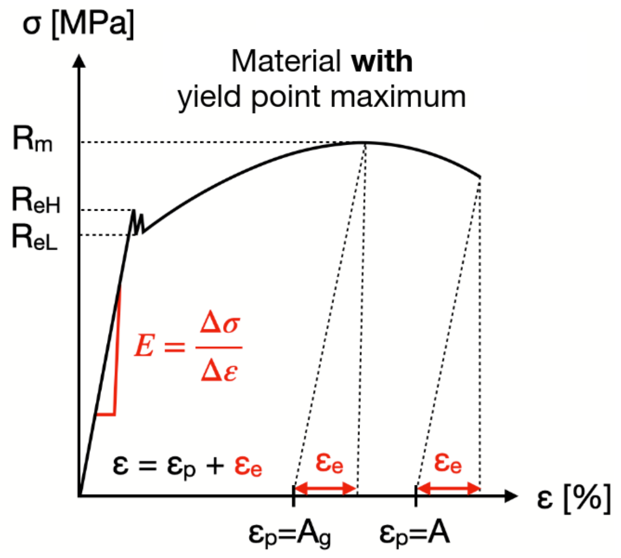
- Upper Yield point R_{eH}: ferritic structural steels (BCC)
- 0.2% Yield Stress $R_{p0.2}$: most other metals and alloy

7.3.2 Graphical representation



Without the maximum yield point:

- $\sigma_{max} = R_{p0.2}$ (0.2% yield stress)



With the maximum yield point:

- $\sigma_{max} = R_m$
- Upper yield point R_{eH}

7.4 Young's modulus and Characteristic Strength Values

7.4.1 Young's modulus *E*

The Young's modulus E is measured as the slope in the linear-elastic range:

$$\boxed{E = \frac{\Delta\sigma}{\Delta\varepsilon} \text{ in } [\mathrm{N/mm^2} \text{ ; } (\mathrm{MPa})] \text{ or } [\mathrm{kN/mm^2} \text{ ; } (\mathrm{GPa})]}$$

7.4.2 Yield stress *R*

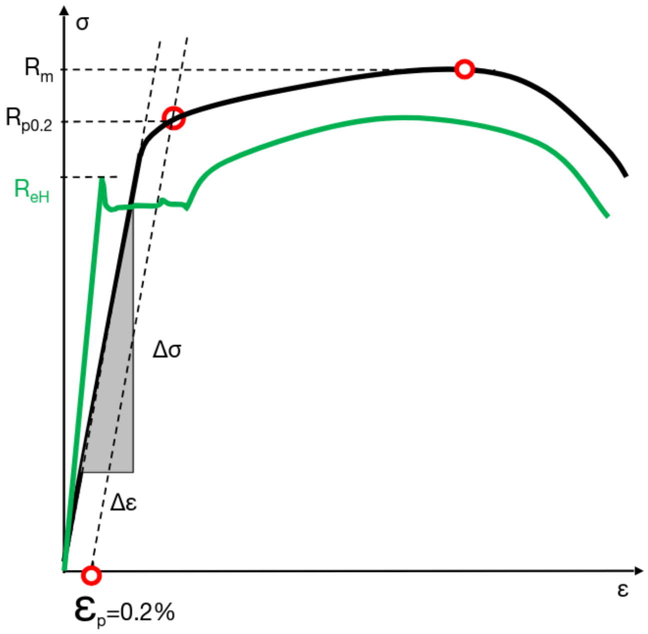
Yield stress R is the stress, expressed in MPa, at which plastic deformation begins:

- 0.2% Yield stress $R_{p0.2}$ corresponds to the stress at a plastic strain of $\varepsilon_p = 0.2\%$
- Upper yield point R_{eH} corresponds to the maximum stress observed at the onset of yielding, mainly in ferritic structural steels

7.4.3 Tensile strength R_m

It corresponds to the stress at the maximum of the stress-strain curve

7.4.4 Graphical representation

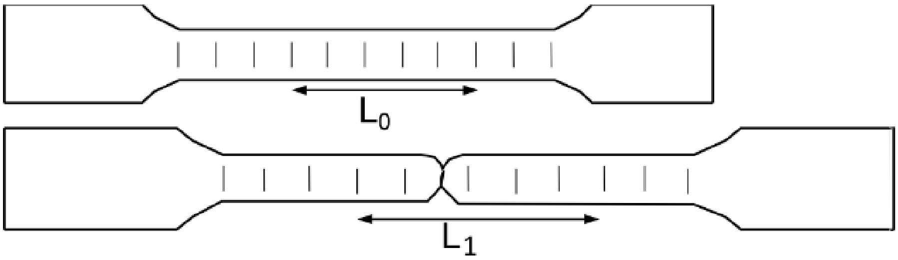


Note: representation not scaled; the elastic region is drawn much too flat

7.5 Characteristic Ductility values

7.5.1 Fracture Strain A

Plastic strain at fracture is defined with respect to the initial specimen length L_0 (e.g.: $L_0 = 50\text{mm}$ is reported as $A_{50\text{mm}}$)



$$\text{Plastic strain at fracture: } A = \frac{L_1 - L_0}{L_0} = \varepsilon_{\text{p, fracture}}$$

7.5.2 Uniform Strain A_g

A_g corresponds to the plastic strain at maximum load before necking begins. It is very important for metal forming.

7.5.3 Contraction at fracture Z

It is the reduction of the cross-sectional area after fracture:

$$\boxed{Z = \frac{\Delta S}{S_0} = \frac{(S_1 - S_0)}{S_0}}$$

7.6 True Stress and True Strain

7.6.1 True stress $\sigma*$

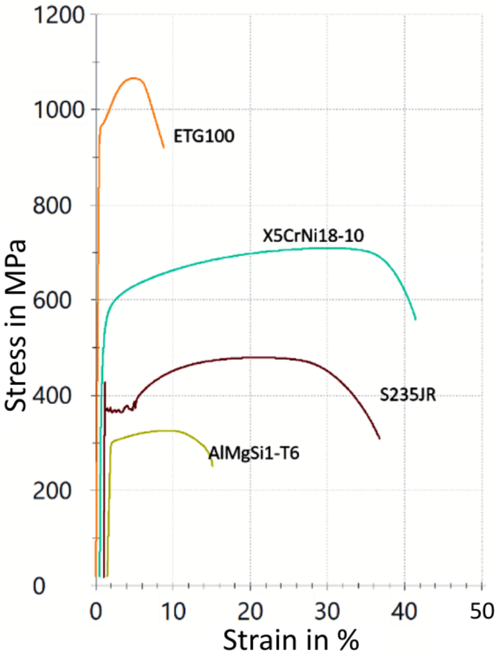
True stress is the force related to the **true** cross-section (which is constantly contracting):

$$\boxed{\sigma^* = \sigma\,(1+\varepsilon)}$$

7.6.2 Ture strain $\varepsilon*$

True strain is the change in length relative to the **true** length (which is constantly extending):

$$\boxed{\varepsilon^* = \ln\,(1+\epsilon)}$$



7.7 Polymers Tensile test

- Characteristic values depend on test speed and temperature (0.125-500 mm/min).
- Creep occurs already at room temperature: creep tests and isochronus stress-strain diagrams are really relevant
- At high temperature and low strain rate: strength values and Young's modulus decrease, while characteristic strain values increase
- Characteristic values differ from materials:
  - Secant modulus E (determinated between $\varepsilon = 0.05\%$ and 0.25%)
  - Yield stress σ_y and yield strain ε_y
  - Fracture stress σ_b and fracture strain ε_b

7.8 Summary of tensile test

- Stress-strain behavior is determined on a specimen (rod, round, flat). Standard: DIN EN EN ISO 6892
- Force and elongation are measured and converted into stress σ and strain ε
- The resistance of a material to plastic deformation or fracture is referred to as its **strength**

From the stress-strain curve, the following characteristic values can be identified:

7.8.1 Characteristic stress values

- 0.2% Yield Strength $\mathrm{R_{p0.2}}$ (for ferritic structural steels: Upper Yield Point R_{eH}): defines the onset of plastic deformation. This is the most important value for construction and design
- Tensile strength $\mathrm{R_m}$: characterizes the resistance to fracture

7.8.2 Characteristic strain values

- Fracture strain A
- Uniform strain A_g
- Contraction at fracture Z
- $r-$ and $n-$values (relevant in metal forming)

7.8.3 Elastic range

- Young's modulus E (Hooke's law, elastic slope)
- Poisson's ratio ν

8 Other quasi-static mechanical tests

8.1 Bending test

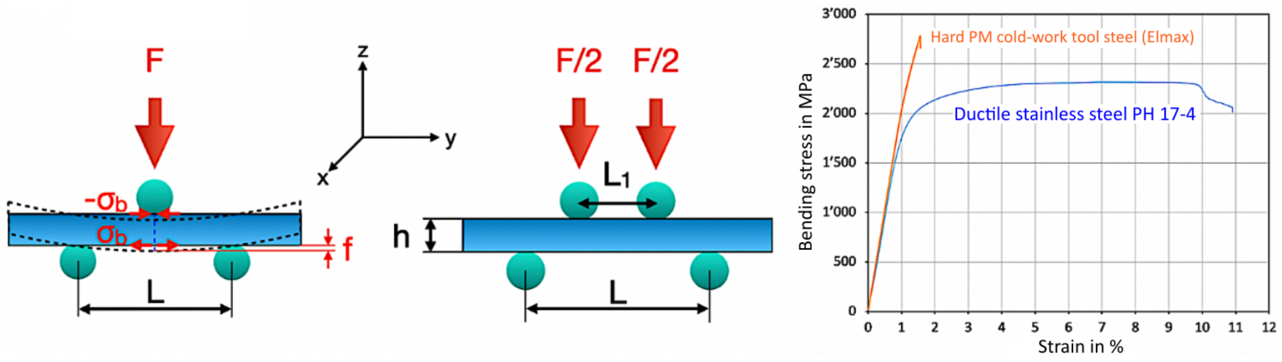
8.1.1 Flexural strength (bend strength) σ_b

The bend strength is the peripheral edge stress σ_b in the fracture point:

$$\boxed{\sigma_b = \frac{3FL}{2bh^2} = \frac{3F(L-L_1)}{2bh^2}}$$

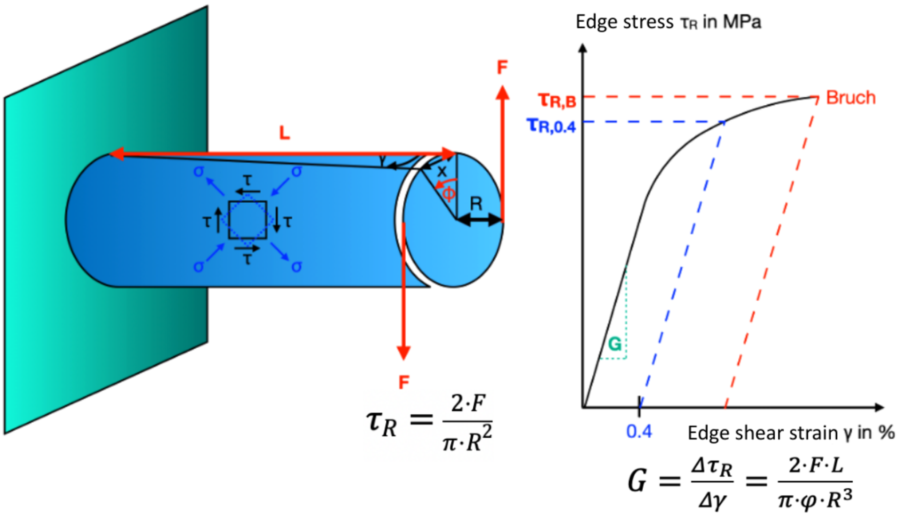
The Young's modulus E is then calculated as:

$$\boxed{E = \frac{L^3 \cdot F}{4bh^3 \cdot f}}$$



8.2 Torsion test

- Less significant than tensile or bending tests
- Peripheral edge shear stress τ_R at fracture = torsion strength $\tau_{R,B}$
- A plastic shear strain at the peripheral edge of 0.4% corresponds to a plastic strain of 0.2% in tensile tests
- The 0.4% torsion strength $\tau_{R,0.4} > R_{\mathrm{p}0.2}$ from tensile tests
- $\boxed{\tau_{R,0.4} \simeq 0.58 \cdot R_{\mathrm{p}0.2}}$



$$\tau_R = \frac{2 \cdot F}{\pi \cdot R^2}$$

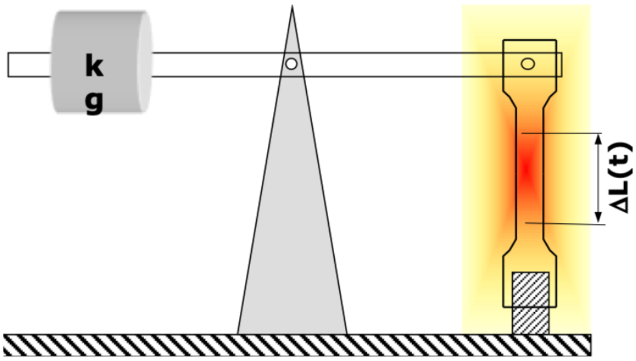
$$G = \frac{\Delta \tau_R}{\Delta \gamma} = \frac{2 \cdot F \cdot L}{\pi \cdot \varphi \cdot R^3}$$

8.3 Creep and Relaxation Tests (High temperatures)

- Creep occurs under constant stress; relaxation occurs under constant strain
- At room temperature, the static strength of metals is generally not time-dependent. Exceptions include: pure aluminum, and very strong metal such as tin and lead
- At elevated temperatures, strength becomes time-dependent and also influenced by test speed. Under constant load, strain does not remain constant but changes with load and time
- Materials with good creep resistance include ferritic and austenitic steels, cast steels, and nickel alloys. These are used above 400°C in applications such as steam boilers, steam turbines, chemical reactors, industrial furnaces, gas turbines, and aircraft engines
- Creep and relaxation tests are essential for evaluating heat-resistant materials, alongside tensile and fatigue tests at elevated temperatures.

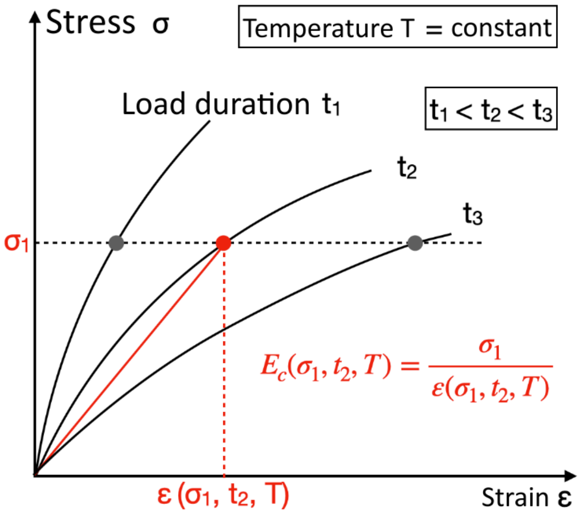
8.3.1 Creep test

The creep test is easier to perform than the relaxation test, since it applies a constant load and the resulting strain is easily measurable.



8.4 Isochronus $\sigma - \varepsilon-$Diagram for Polymers

- In creep tests, strain increases under constant stress (for many polymers this occurs even at room temperature)
- Multiple creep curves can be combined into an isochronus $\sigma - \varepsilon-$diagram
- For different temperatures, a separate diagram is created for each temperature



$$\boxed{E_c\left(\sigma, t_2, T\right) = \frac{\sigma_1}{\varepsilon\left(\sigma_1, t_2, T\right)}}$$

Part III

Steel - Technology and applications

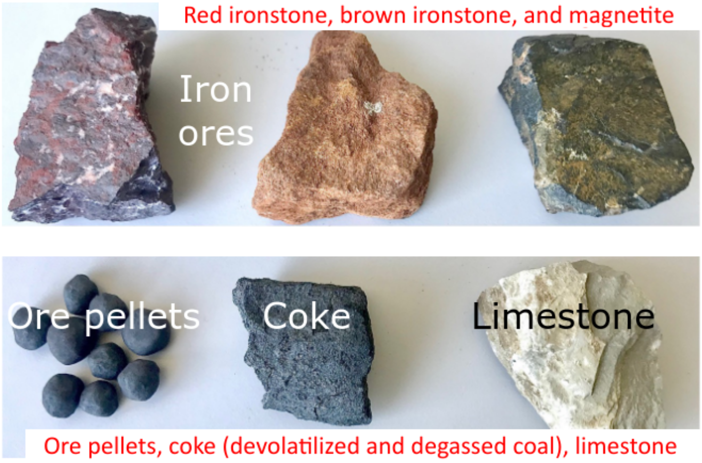
Steel is a Carbon-iron alloy and is the most important construction material:

- All Fe-C alloys with $\leq 2.1\%$ carbon (+ further alloying elements)
- Very good properties, adjustable over a large range:
  - Strength, ductility, toughness, formability, machining, weldability
  - Many possibilities of heat treatments (polymorphism of iron)
- Innovation boost: about 75% of all steels used today have been developed in the last 20 years
- China dominates steel market (>50% of world production)
- Cost-effective (large variety of global suppliers, availability of raw materials)

9 Steel technology

9.1 Blast furnace and Pig iron

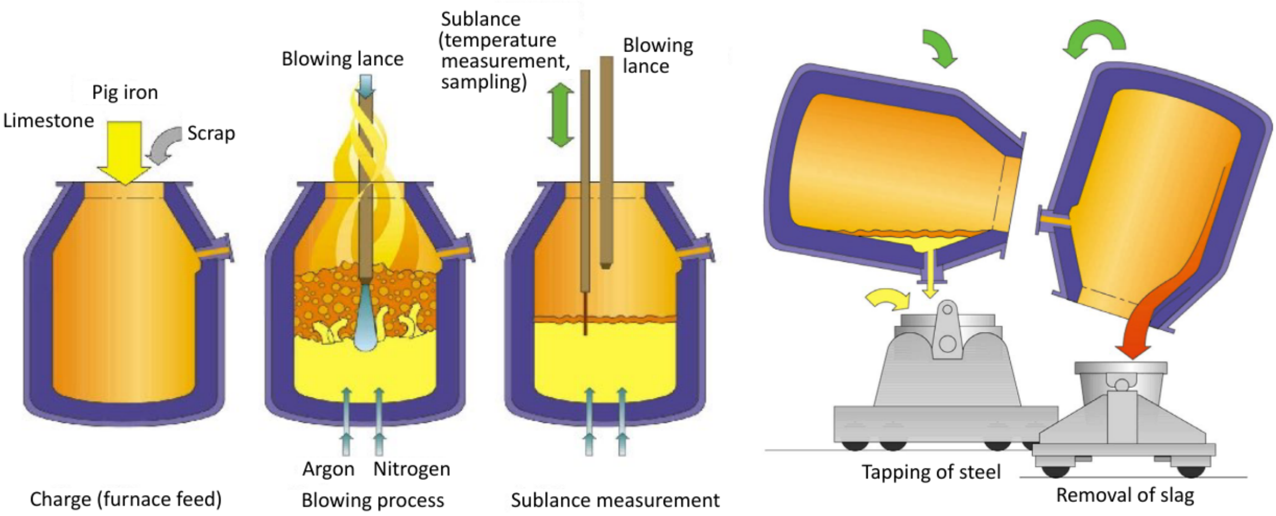
- Process: reduction of iron oxide with coke $Fe_2O_3 + 3C \rightarrow 2Fe + 3CO$
- Product: pig iron (3-5% C, also contains Mn, Si, S, P)
- Furnace dimensions: ~30m tall, ⌀10-14 m
- Typical input/output per day:
  - 16'000 t ore, 4'500 t coke, 14'000 t air
  - → 10'000 t pig iron, 3'000 t slag, 22'000 t exhaust gas



9.2 Conversion to Crude Steel

9.2.1 Oxygen-Blown Converter (OBC)

- Pig iron (>6% C) reformed to crude steel (<2% C)
- Pure oxygen burns off the excess carbon and other impurities
- Main process:
  - Oxygen-blown converter (OBC, LD process)
  - Electric furnace (EF, arc furnace, often using scrap or direct reduced iron (DRI) as input)
  - (Historically: open-hearth furnace (OHF), now obsolete)
- Continuous casting dominates (>30% worldwide production)



Oxygen-blown converter (OBC) process

9.2.2 Electric Furnace (EF)

In Europe, about 39% of crude steel is produced in electric furnaces (EF), while in the World, it is about 25.8%.

9.3 Secondary metallurgy (Ladle metallurgy)

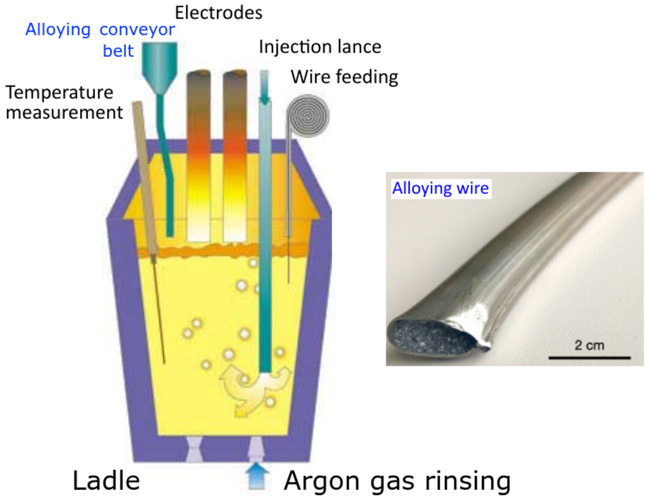
9.3.1 Purifying and alloying of the crude steel

Procedure:

- **Deoxidation**: decreasing soluble oxygen content during solidification, in order to avoid gas inclusions and splashes
- **Removal of impurities**: Gases and solids are rinsed out with Argon
- **Alloying**: Alloying wires, similar to tubes, are added to the ladle (usually via conveyor belt)
- **Temperature adjustment**: Casting temperature is adjusted by adding scrap or iron granules
- The ladle discharge is mostly continuous casting (strand casting, 88% of the annual world production)

Special processes for archiving maximum purity:

- Electroslag remelting (ESR)
- Vacuum arc remelting (VAR)
- Powder metallurgy (PM)



Ladle metallurgy process

9.3.2 Important alloying elements

Improvement of hardenability
The improvement of hardenability prevents the diffusion of Carbon during quenching.
Most important elements: Mn, Cr, Ni, Mo, V, Si

Fine grain
Al, V, Ti, Nb in small quantities as nucleation agents (nitrides) in fine-grained structural steels.
V for grain refinement in QT steels, and **Co** for hindering grain growth in high-speed steels (HSS).

Corrosion resistance
Cr, Cu, Ni, Si, Mn (all approx. $\lesssim 0.5 - 1\%$) to slow down the surface corrosion of steels in atmospheres and water.
Cr (>12%) and **Ni** for stainless steels (e.g. AISI 304, 316).
Mo and **N** for pitting corrosion resistance in stainless steels.
Ti, Nb, Ta against intercrystalline corrosion in stainless steels after welding.

Wear and Heat resistance
Special carbide formers: **Cr** (>1%), **Mo, V**
Special nitride formers: **Al, V, Ti, Nb, Mo, Cr**

Scale resistance
Against oxidation (scale formation), stable oxide layer against surface burn-off: **Cr, Al, Si**

9.3.3 Resume of alloying elements functions

Function	**Alloying elements**
Hardenability	Mn, Cr, Ni, Mo, V, Si
Grain refinement	Al, V, Ti, Nb
Corrosion resistance	Cr (>12%), Cu, Ni, Si, Mn, Mo, N ($\lesssim$0.5-1%)
Wear/heat resistance	Cr (>1%), Mo, V, Al, Ti, Nb, Mo
Scale resistance	Cr, Al, Si

9.3.4 Electroslag remelting process (ESR)

Principle

- Electric remelting furnace is used for refining semi-finished steel products after continuous casting
- Steel is remelted through a layer of **reactive slag** under alternating current (AC)

Functions of the reactive slag

- Removes impurities (e.g. P, S, O, N, H), and non-metallic inclusions
- Acts as refining and protective medium

Solidification

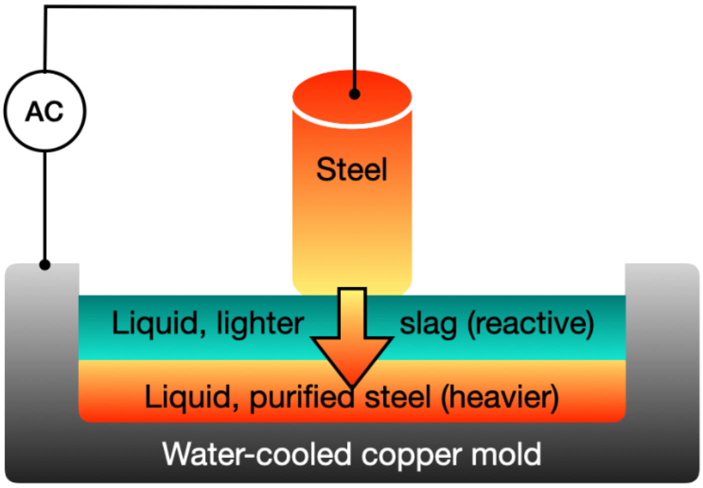
- Melt droplets pass through slag and solidify in a **water-cooled copper mold**
- Rapid solidification procedures:
  - Fine-grained structure
  - Homogeneously distributed carbides

Applications

- Production of **high-purity steels** for: Toolmaking, Medical technology, Watch and precision industries, Aerospace

Alternative method

- Powder metallurgy (PM) can archieve similar levels of purity



Electroslag remelting process (ESR)

9.4 Continuous casting

- **Slabs**: Semi-finished product for rolling sheets (coils), foils, plates
- **Billets**: Semi-finished product for rolling wires, rods, profiles
- Wires → screws, nails, spheres, smaller rods
- Rods → shafts, axles, larger profiles
- Cold drawing → good surface quality, high precision
- ETG → high strength
- Most steel (>90%) is strand-cast

9.5 Recycling and Green Steel

- Direct hydrogen reduction instead of blast furnace → Up to 95% lower CO_2 emissions, but high costs
- Hydrogen supply:
  - H_2 produced by electrolysis of water
  - Powered with renewable electricity (wind, solar)
- Iron ore reduction
  - Iron ore directly reduced with **green hydrogen** (DRI) to forme sponge iron
  - By-product: **water vapor** instead of CO_2
- Steel production
  - Sponge iron charged to an **electric arc furnace** (EAF) to produce crude steel
  - Furnace operated with green electricity

9.6 Summary of Steel Technology

9.6.1 Blast furnace

- Iron ore reduced to **pig iron** in a blast furnace

9.6.2 Crude steel production

- Pig iron refined to **crude steel** by reducing carbon content
- Oxygen-Blown Converter (**OBC**): refining with oxygen
- Electric Furnace (**EF**): melts scrap steel or direct-reduced iron (sponge iron) to crude steel

9.6.3 Secondary metallurgy

- Crude steel further purified and adjusted to final composition in a ladle furnace
- **Processes**:
  - Deoxidation (chemical or vacuum)
  - Advanced purification (electroslag remelting (ESR), vacuum arc remelting (VAR), powder metallurgy (PM))
  - Alloying additions

9.6.4 Semi-finished products

- Produced mainly by **continuous casting** (slabs, billets)
- Formed into sheets, plates, wires, rods, pipes, and profiles by hot or cold rolling/drawing

10 Microstructure formation

10.1 Polymorphism of Iron

10.1.1 δ-iron

δ-iron is a phase of iron with a BCC structure. It is stable above 1392°C, and it's not ferromagnetic. Has a limited technical relevance.

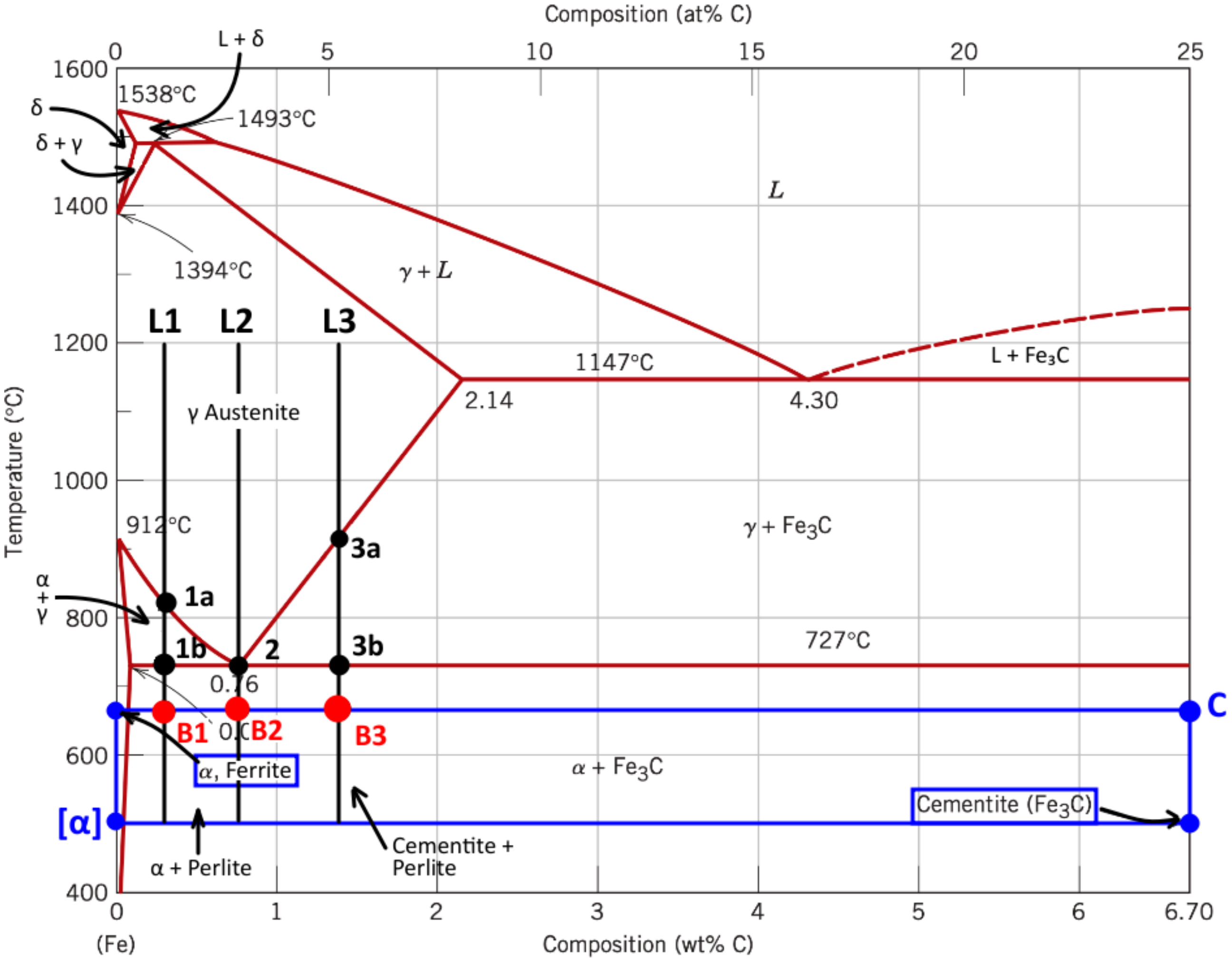
10.1.2 γ-iron (austenite)

γ-iron, also called austenite, is a phase of iron with a FCC structure. It is stable between 911 - 1392°C. It's not ferromagnetic, and is soluble up to 2% C, 100x more than α-iron. Its high solubility is due to larger interstitial sites and reduced lattice distorsion from carbon atoms.

10.1.3 α-iron (ferrite)

α-iron, also called ferrite, is a phase of iron with a BCC structure. It's stable below 911°C. It's not ferromagnetic between 769-911°C, but it becomes ferromagnetic below the **Curie temperature**, so <769°C. It has very low carbon solubility, maximum 0.02% C.

10.2 Metastable iron - iron carbide phase diagram



10.2.1 Phase diagram explaination

The Fe-Fe_3C phase diagram shows the equilibrium between iron and cementite (Fe_3C) in steels and cast irons under slow cooling. It is called metastable because Fe_3C is not the most stable carbide (graphite is), but cementite forms under typical industrial conditions.

Symbol	Phase	Description
α	Ferrite	BCC structure, very low carbon solubility (≤ 0.022 wt% C at 727°C), soft and ductile
γ	Austenite	FCC structure, higher carbon solubility (≤ 2.14 wt% C at 1147°C), though and formable
δ	Delta ferrite	BCC form stable only at high temperatures ($>$ 1394°C)
$\mathbf{Fe_3C}$	Cementite	Hard, brittle iron carbide with 6.70 wt%
L	Liquid phase	Molten iron-carbon alloy

10.3 Microstructure formation of Steel (Slow Cooling)

- L_1: hypoeutectoid steel, 0.35% C (e.g. structural steel)
- L_2: eutectoid steel, 0.8% C (e.g. cable of car wires before heat treatment)
- L_3: hypereutectoid steel, 1.4% C (e.g. ball bearing spheres before hardening)

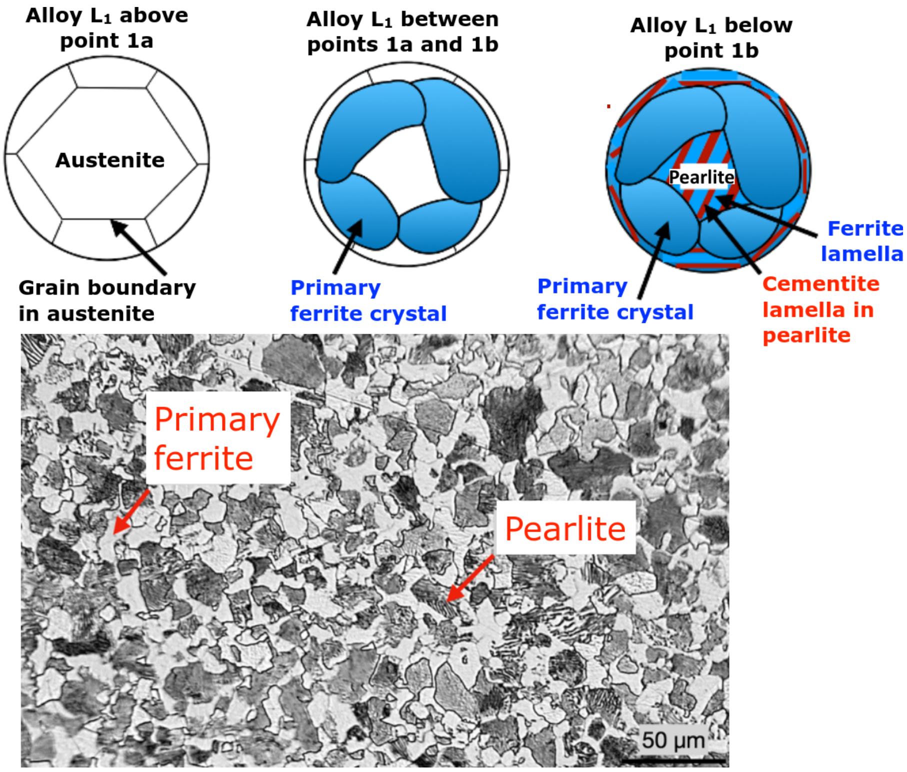
Summary of key reactions

Type	**Composition range wt% C**	**Reaction**	**Temperature**	**Resulting microstructure**
Eutectic	4.3	$L \rightarrow \gamma + \mathrm{Fe_3C}$	1147°C	Ledeburite (austenite + cementite)
Hypoeutectic	< 4.3	$L \rightarrow \gamma + L_{\mathrm{eutectic}} \rightarrow \gamma + \mathrm{Fe_3C}$	< 1147°C	Primary austenite + ledeburite
Hypereutectic	> 4.3	$L \rightarrow \mathrm{Fe_3C} + L_{\mathrm{eutectic}} \rightarrow \mathrm{Fe_3C} + \gamma$	< 1147°C	Primary cementite + ledeburite
Eutectoid	0.8	$\gamma \rightarrow \alpha + \mathrm{Fe_3C}$	727°C	Pearlite (ferrite + cementite)
Hypoeutectoid	< 0.8	$\gamma \rightarrow \alpha_{\mathrm{primary}} + \mathrm{pearlite}$	< 727°C	Primary ferrite + pearlite
Hypereutectoid	> 0.8	$\gamma \rightarrow \mathrm{Fe_3C_{primary}} + \mathrm{pearlite}$	< 727°C	Primary cementite + pearlite

10.3.1 Hypoeutectoid steel L_1

Hypoeutectoid steels contain less than 0.8 wt% carbon. During **slow cooling**, they form a mixture of **ferrite and pearlite**. Ferrite appears first during solid-state transformation and is therefore called **primary ferrite** (proeutectoid).

Properties
Soft, ductile steel with good weldability and formability, commonly used as structural steel.



Microstructure at room temperature of primary ferrite and pearlite

10.3.2 Eutectoid steel L_2

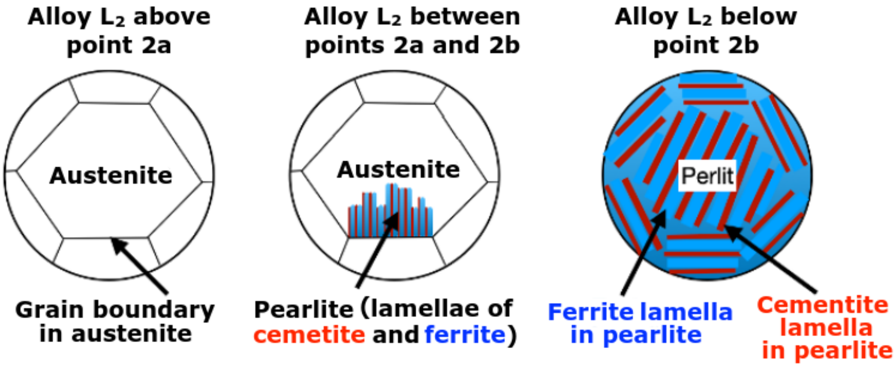
Eutectoid steel contains exactly 0.8 wt% carbon, corresponding to the eutectoid composition in the Fe-Fe_3C phase diagram. At the eutectoid temperature (727°C), **austenite (γ)** transforms completely into **pearlite**, a finely layered mixture of **ferrite (α) and cementite (Fe_3C)**.

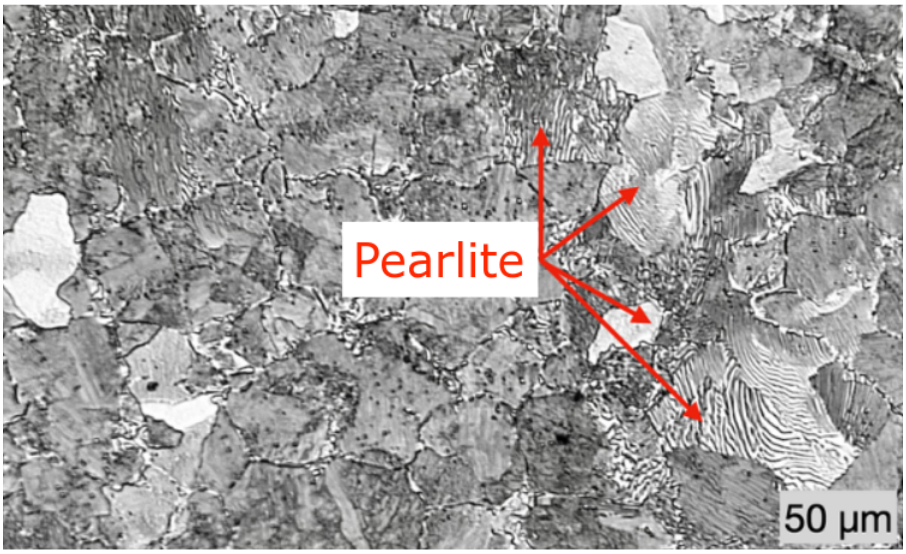
$$\gamma \xrightarrow[727^\circ\mathrm{C}]{} \alpha + \mathrm{Fe_3C}$$

Final microstructure at Room Temperature
The microstructure is 100% pearlite, consisting of:

- **Ferrite lamellae (*alpha*)**: soft, ductile phase forming the light layers
- **Cementite lamellae Fe_3C**: hard, brittle phase forming the dark layers

The alternating lamellar structure provides a balance of strength and ductility, characteristic of unalloyed eutectic steel.





Microstructure at room temperature of eutectoid steel after slow cooling

Result
Eutectoid steel exhibits a uniform pearlitic structure, combining moderate hardness with good toughness. It serves as a base for many steels that are later hardened or tempered by heat treatment.

10.3.3 Hypereutectoid steel L_3

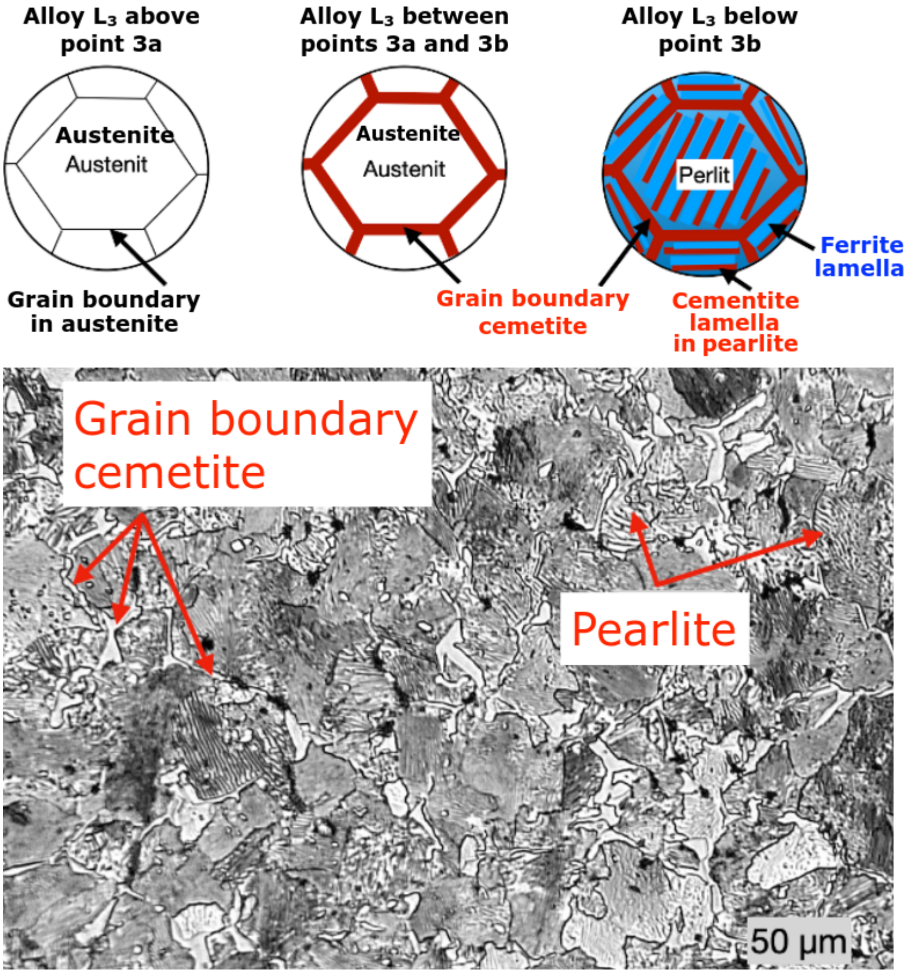
Hypereutectoid steels contain more than 0.8 wt% carbon. During slow cooling, **cementite Fe_3C** precipitates first at austenite grain boundaries. The remaining austenite transforms into **pearlite** at the eutectoid temperature.

$$\gamma \rightarrow \mathrm{Fe_3C}_{\text{grain boundary}} + (\alpha + \mathrm{Fe_3C})_{\text{pearlite}}$$

Final microstructure at Room Temperature
Final components:

- **Grain boundary cementite** (proeutectoid cementite): hard and brittle. It forms before eutectoid reaction and outlines prior austenite grains
- **Pearlite**: lamellar mixture of ferrite and cementite, formed from eutectoid reaction at 727°C

Total structure: **grain boundary cementite + pearlite**

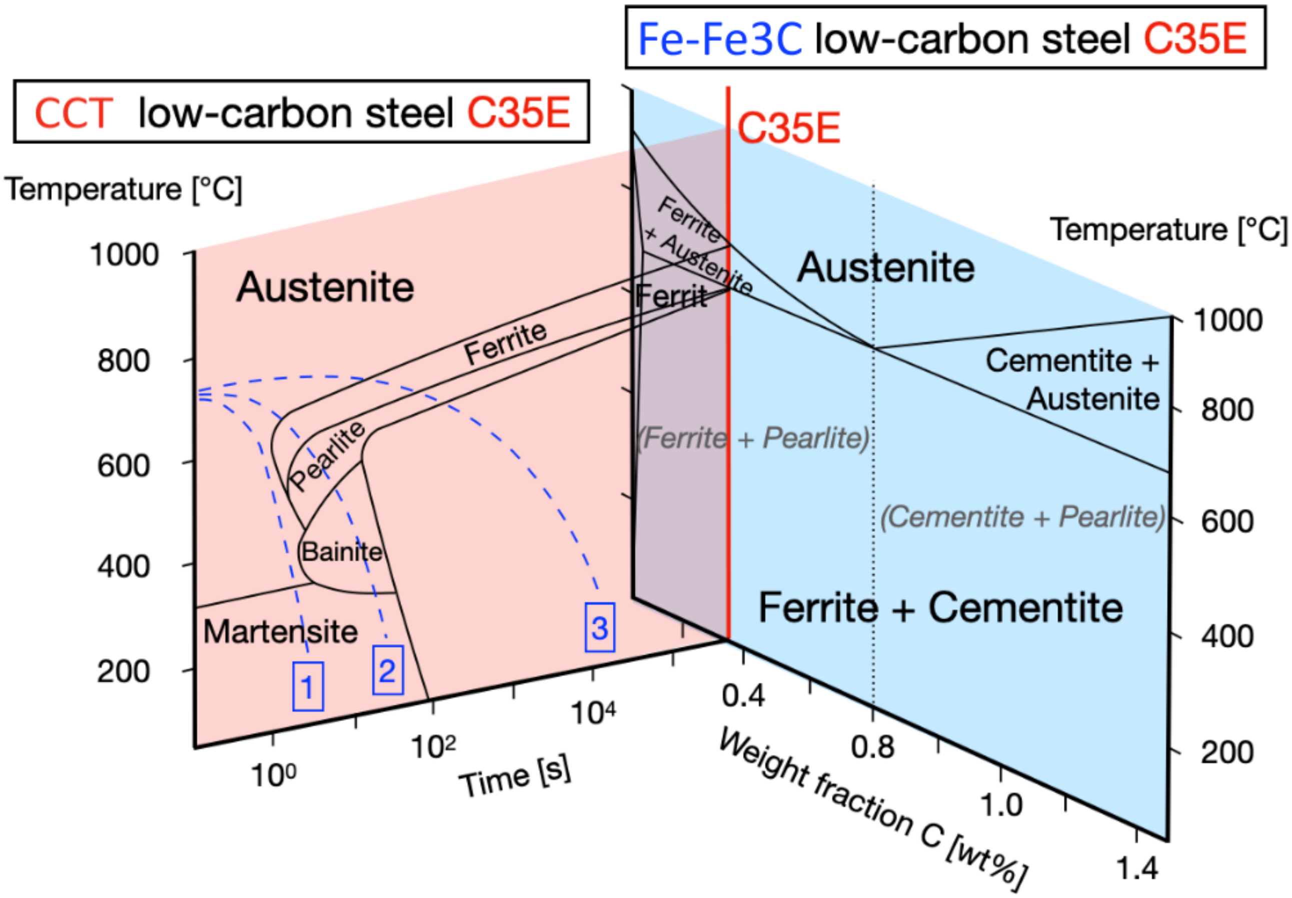


Microstructure at room temperature of hypereutectoid steel after slow cooling

Result
Hard and wear-resistant, suitable for applications requiring high surface hardness and fatigue strength (e.g. ball bearings, cutting tools).

10.4 Faster Cooling / Quenching

Fast cooling of steel changes the transformation behavior compared to equilibrium cooling. In such cases, the Continuous-Cooling Transformation (CCT) diagram is used.



Fast cooling:

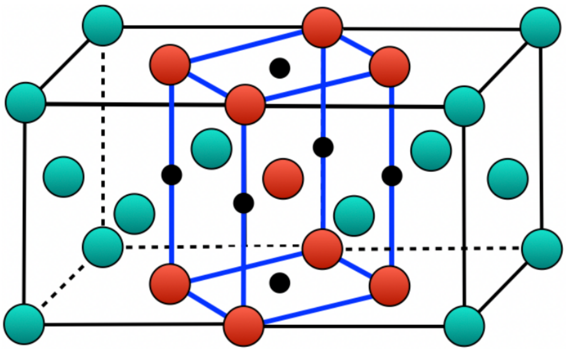
- Transformation temperatures shift to lower values
- Pearlite become finer and forms over a wider temperature range instead of only at 727°C
- **Martensite and bainite can form**

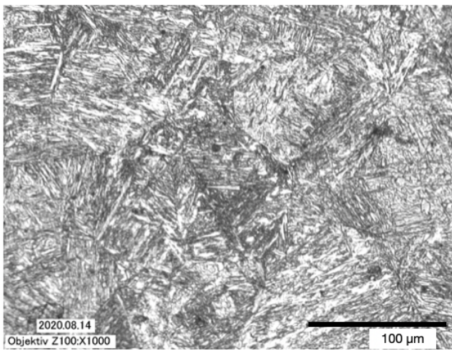
10.4.1 Difference between CCT and Iron-Iron Carbide Phase Diagram

Diagram	**Description**	**Use case**
CCT diagram	Shows phase transformations under continuous cooling	Required for realistic heat-treatment conditions
Fe-Fe_3C diagram	Shows equilibrium (slow-cooling) transformations	Valid only for very slow cooling / equilibrium

10.5 Martensite

- Very fast cooling (quenching) of austenite produces a martensitic transformation
- Diffusion does not occur, so neither ferrite nor pearlite can form
- Lattice shear of FCC austenite produces tetragonal body-centered martensite





10.6 Bainite

Rapid cooling to an intermediate temperature range (250-500°C), slower than for martensite or pearlite, produces bainite:

- Combined shear and limited diffusion with cementite precipitation
- **Higher strength** than pearlite, **more ductile** than martensite
- Suitable for high-performance components and tools

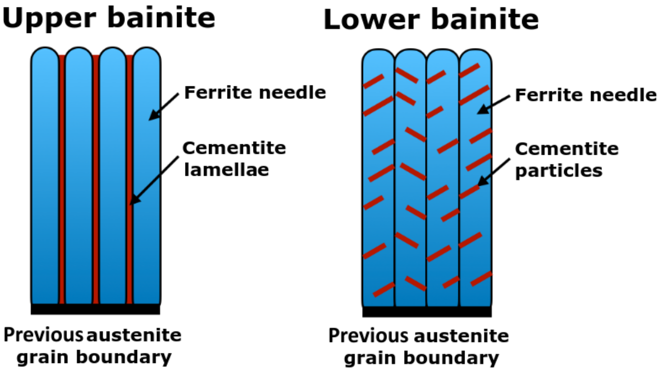
10.6.1 Structure

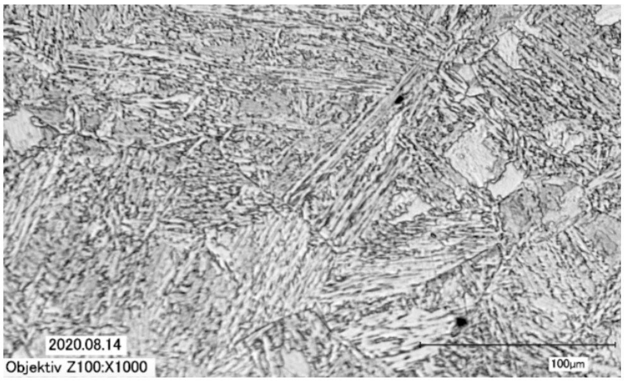
Upper bainite

- Forms at higher bainitic temperatures (350-500°C)
- Ferrite needles with cementite lamellae mainly at ferrite boundaries

Lower bainite

- Forms at lower bainitic temperatures (250-350°C)
- Ferrite needles with fine cementite particles inside the ferrite





10.7 Continuous-Cooling Transformation Diagram (CCT)

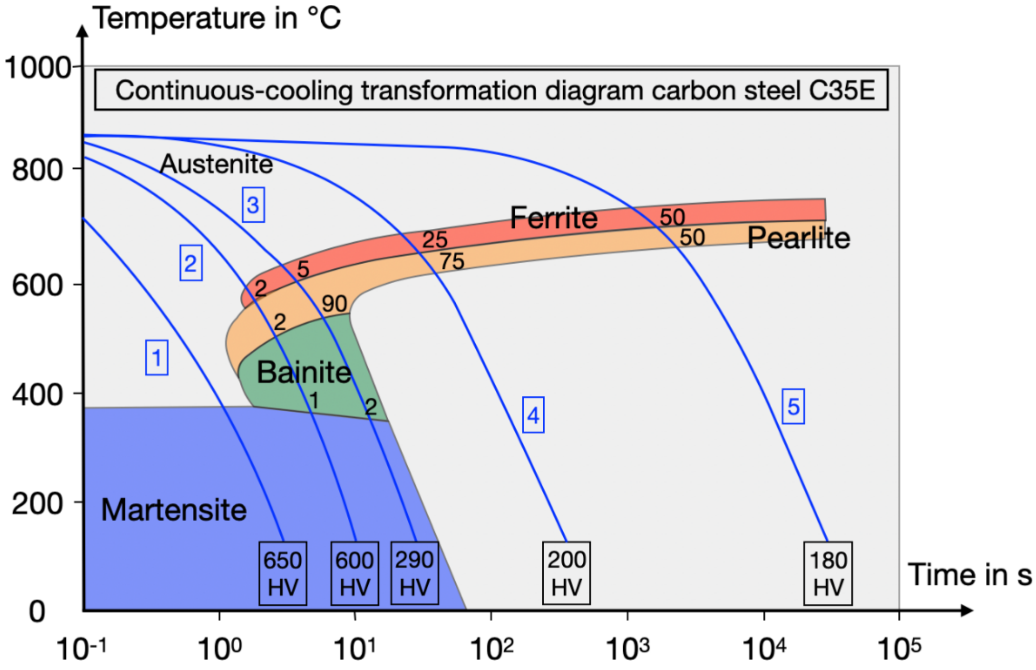
The CCT diagram shows phase transformation during continuous cooling.

10.7.1 Carbon steel C35E CCT

- For C35E steel (0.35 wt% C), only small amounts of bainite form
- Bainite forms only within a narrow temperature-time range
- Higher cooling rates produce martensite, slower cooling produces ferrite and pearlite

Resulting hardness for typical cooling paths

- Martensite: about 650-600 HV
- Bainite: about 290 HV
- Ferrite-pearlite: about 200-180 HV



10.7.2 Vickers hardness calculation

$$\boxed{\mathrm{HV} = 0.102 \cdot F \cdot \frac{2\cos(22^\circ)}{\left(\frac{d_1 + d_2}{2}\right)^2}}$$

where d_1, d_2 are the diagonals of the indentation in mm, and F is the applied force in N.

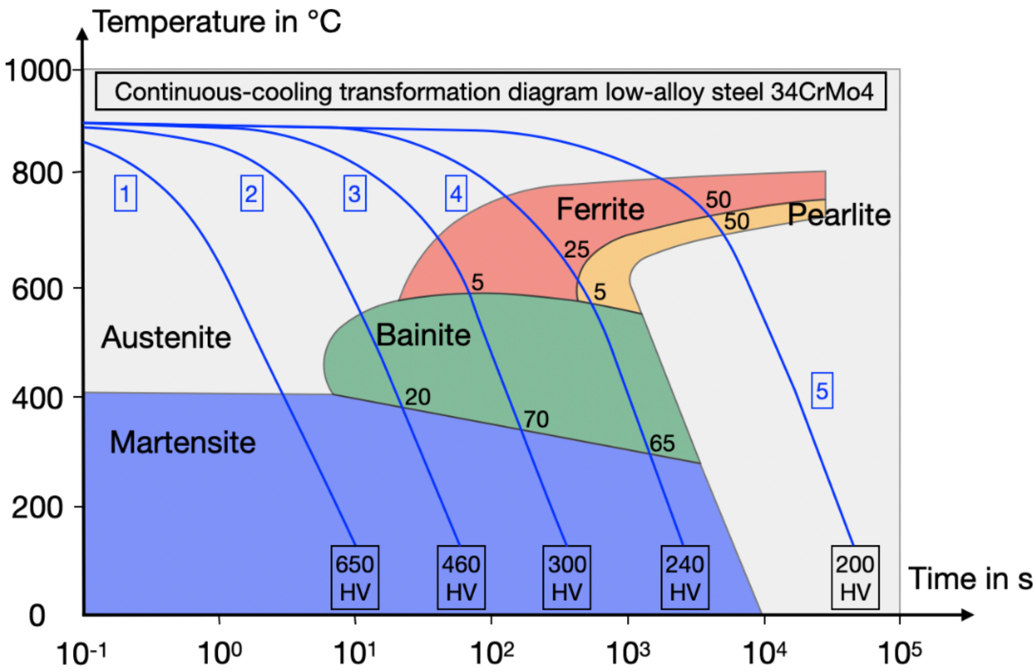
10.7.3 Low-alloyed (Mild) Steel 34CrMo4

This alloyed steel contains 0.34 wt% C, 1 wt% Cr, and 0.2 wt% Mo. It has more bainite, higher ductility, greater hardening depth.

- Larger bainite region that in plain-carbon steel
- Increased toughness and ductility compared to martensite
- Greater hardening depth because slower cooling can still produce martensite or bainite

Typical hardness for cooling path

- Martensite: about 650-640 HV
- Bainite: about 300-240 HV
- Ferrite-pearlite: about 200 HV



10.8 Real-life Continuous-Cooling Transformation Diagram (CCT)

The Real-life CCT diagram shows the transformation behavior under real continuous cooling, illustrating transformation ranges for austenite, bainite, pearlite, and martensite.

10.8.1 Carbon steel C45E

Carbon steel C45E requires high cooling rates to form martensite.

- High cooling rate is needed to reach the martensite region
- Hardening depth is limited due to the need for fast cooling
- Maximum martensitic hardness is reached only to about 5 mm depth from the surface

10.8.2 Low-alloyed (mild) steel 42CrMo4

Low-alloy steel 42CrMo4 contains 0.42 wt% C, 1 wt% Cr, and 0.2 wt% Mo. It shows improved hardenability compared to plain-carbon steels. The martensite region is reached at slower cooling rates, and the bainite formation is more likely.

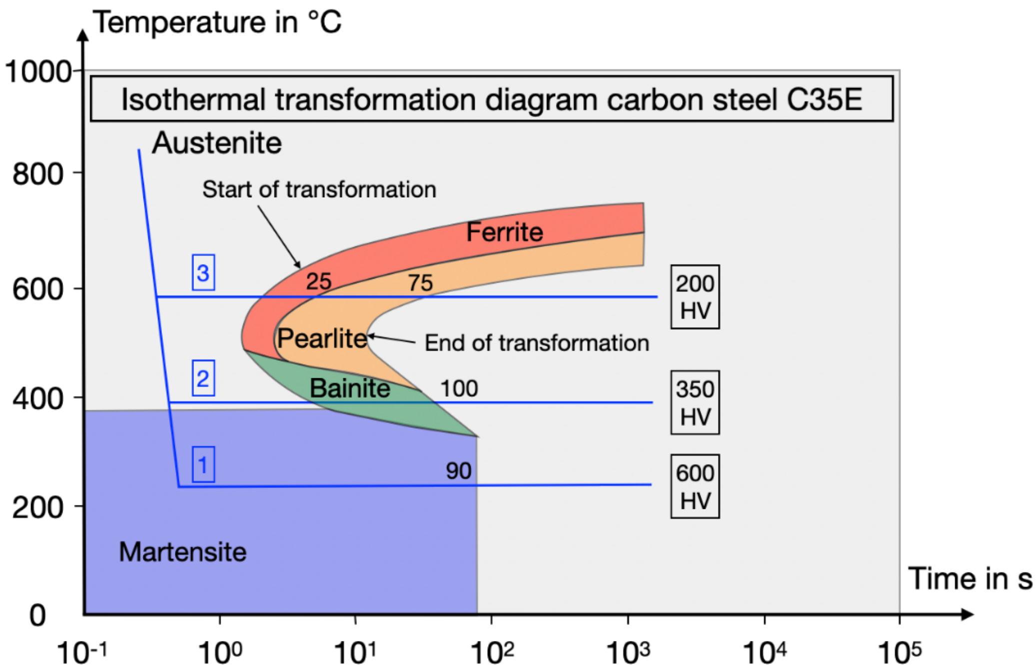
- Slower cooling still produces martensite, which reduces quench distortions
- Hardening depth greater than 5 mm, so thicker parts can be through-hardened or quenched and tempered
- Higher bainite fraction possible, giving a good strength-ductility balance

10.9 Isothermal Transformation Diagram

Bainite can also be formed in carbon steels through isothermal transformation:

- Up to 100% bainite possible in unalloyed carbon steels
- Lower cost than low-alloy steels
- **Use**: automotive parts such as disc springs
- **Cons**: quenching baths often contain liquid lead or toxic salts

Isothermal transformation diagram for C35E shows ferrite, pearlite, bainite, and martensite formation at constant temperatures. **Hardness increases from ferrite-pearlite to bainite to martensite**

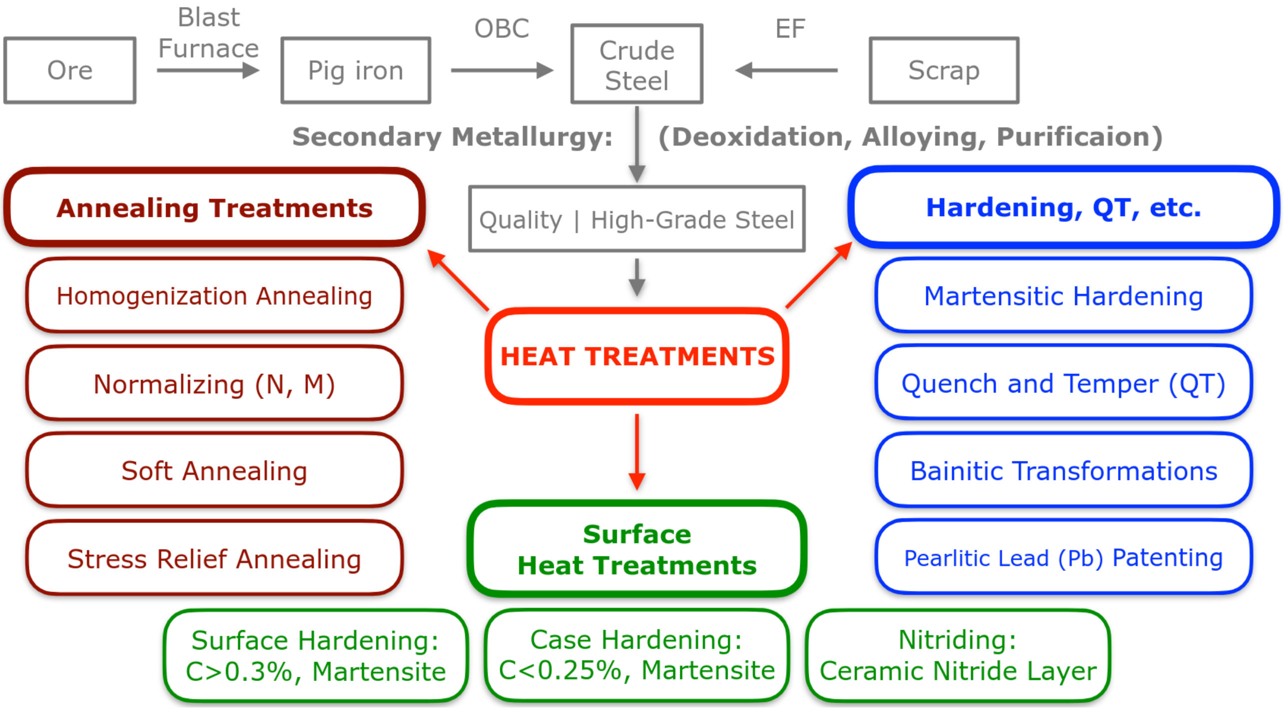


11 Heat treatments

11.1 Heat treatments overview

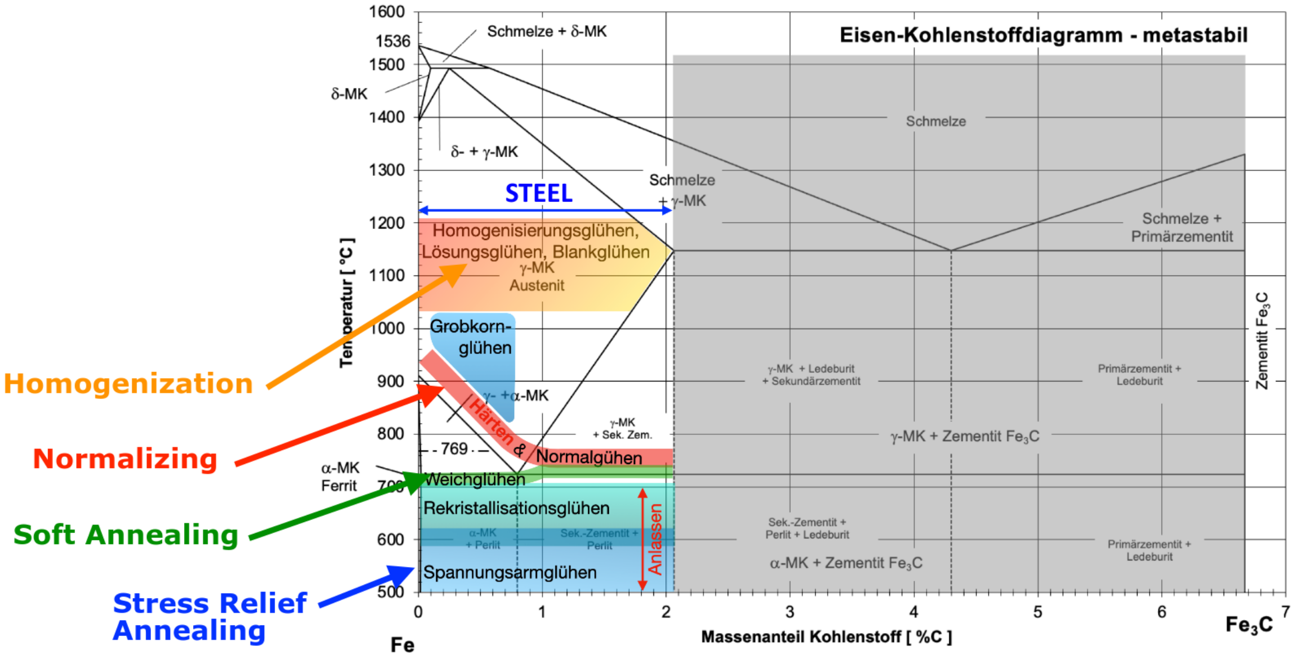
Heat treatments adjust the properties of steel after primary and secondary metallurgy:

- **Annealing treatments** refine microstructure and reduce internal stresses
- **Hardening and tempering** increase strength and wear resistance
- **Surface heat treatments** improve surface hardness while maintaining a tough core



11.2 Typical annealing treatments of steel

Annealing adjusts the microstructure of steel by heating it to a defined temperature range followed by controlled cooling.



Part IV

Hardness and Toughness

12 Hardness

Hardness is a measure of resistance against localizer plastic deformation. It is often considered a minimally invasive way of estimating material strength.

12.1 Hardness testing

12.1.1 Common testing methods

Testing method	**Application**
Vickers (HV)	Universal application
Rockwell (HRC)	Suitable for hard steels
Brinell (HB)	Used for soft steels and aluminum
Berkovich	Used in nanoindentation
Shore A and D	For rubber and plastic

Approximate relation:

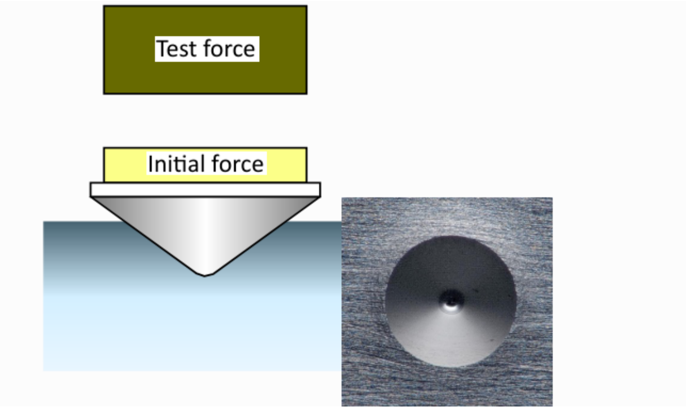
$$\boxed{R_m \approx 3 \times HB \text{ or } HV}$$

12.2 Examples of Hardness Testing Procedures

12.2.1 Indentation depth

Hardness is measured based on how deep the indenter penetrates the material:

- Rockwell C hardness (HRC) for hard metals
- Shore hardness (A,D) for polymers and elastomers

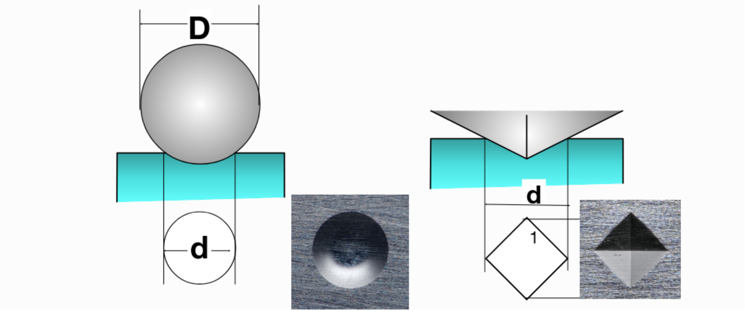


Rockwell hardness testing

12.2.2 Indentation Area

Hardness is determined by the surface area of the indentation left in the material:

- Brinell hardness: Ball indenter for soft metals
- Vickers hardness: Diamond pyramind indenter, universal application



Brinell hardness testing (left), Vickers hardness testing (right)

12.3 Conversion of Hardness values and Tensile strength (Steels)

Hardness values can be correlated to tensile strength. Conversion tables are available to relate HV, HB, and HRC to ultimate tensile strength in MPa.

12.3.1 Hardness - Tensile strength conversion table (Steels)

Tensile strength in MPa	Vickers hardness HV	Brinell hardness HB	Rockwell hardness HRC
	900		67.0
	850		65.6
	800		64.0
	750		62.2
	700		60.1
2180	650	618	57.8
1995	600	570	55.2
1810	550	523	52.3
1630	500	475	49.1
1455	450	428	45.3
1290	400	380	40.8
1125	350	333	35.5
965	300	285	29.8
800	250	238	22.2
640	200	190	
480	150	143	
320	100	95	

13 Notch Impact Toughness

13.1 Impact Notch Toughness Test (Charpy)

- Applied mainly to structural steel (BCC, such as shipbuilding, bridges, oil platforms, pylons)
- The test determines:
  - The transition temperature from ductile to brittle fracture
  - The absorbed impact energy ("notch toughness")
- Failure hypotesis: Crack propagation under sudden, high-impact loads

13.2 Toughness explaination

13.2.1 Material behavior

- **Tough material**: Absorb high energy before fracture (e.g. leather)
- **Brittle material**: Fracture with little energy absorption (e.g. glass)

13.2.2 Energy criterion

- **Ductile fracture**: Defined ductile if absorbes $>$ 27 J of the impact energy
- **Brittle fracture**: Defined brittle if absorbes $>$ 27 J of the impact energy

13.2.3 Stress State dependence

- Monoaxial (tensile test): Material can yield in lateral directions
- Biaxial (pressure vessels): Yield possible in one direction
- Triaxial (notches): No yielding possible, leads more likely to brittle failure

13.3 Charpy Test

The Charpy impact test evaluates a material's toughness by measuring the energy absorbed during fracture under a sudden impact load. It is widely used to determine the ductile-brittle transition temperature of steels and to compare the toughness of different alloys

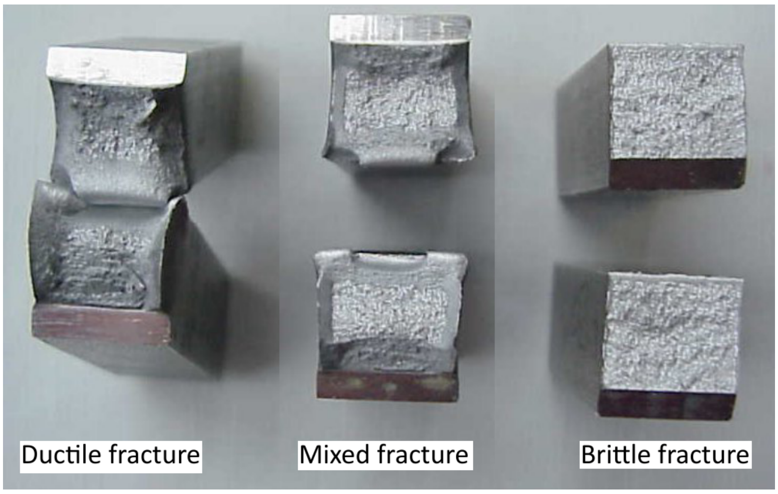
13.3.1 Test setup

- Specimen: Standard rectangular bar, with a V- or U-shaped notch at the center
- The V- or U-notch creates a stress concentration, forcing tracture to start there
- Impact: A heavy pendulum strikes the specimen at the opposite side of the notch, producing fracture
- Measurement: The energy absorbed is read from a calibrated scale linked to the pendulum swing

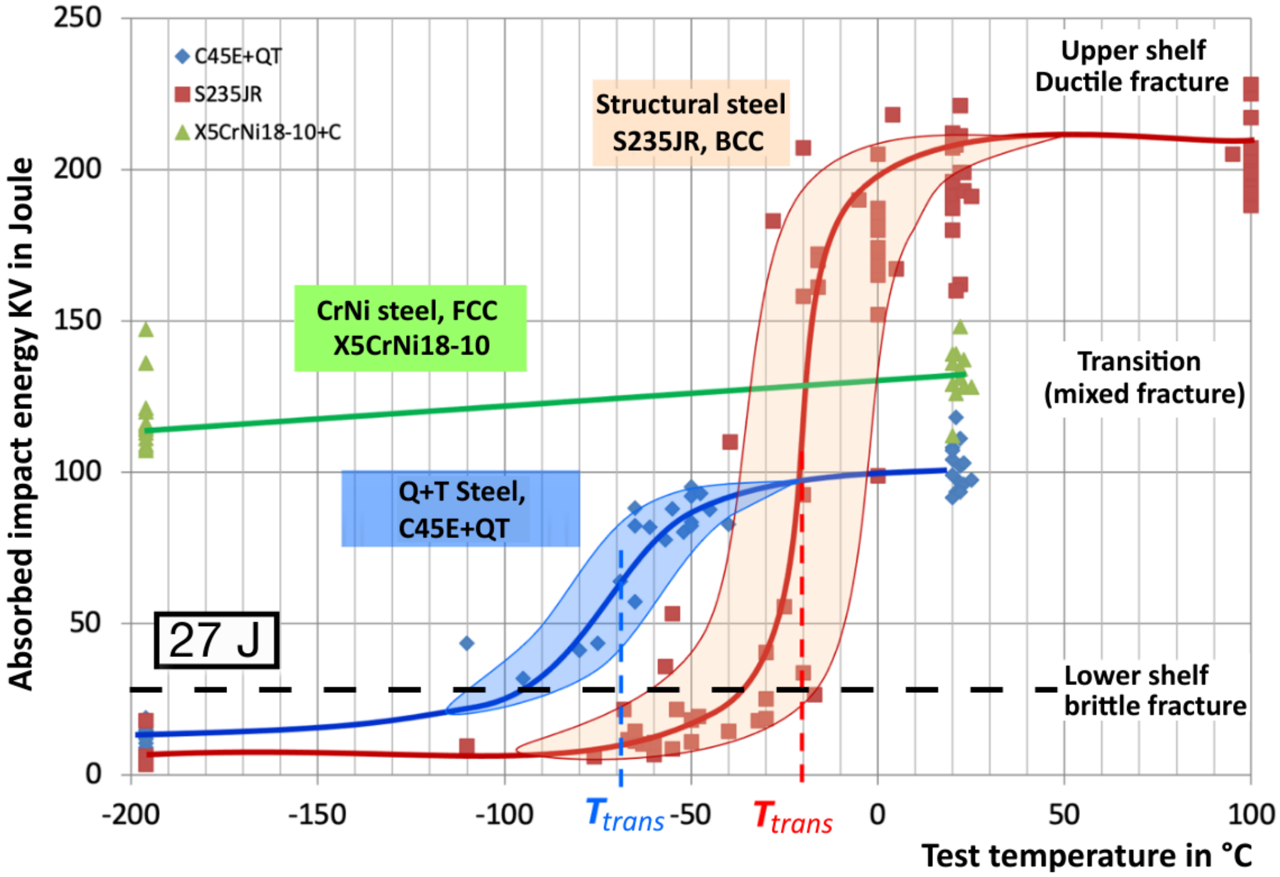
13.3.2 Differences between Charpy and Izod impact tests

	Charpy	**Izod**
Types of Notches	U- and V-Notch	V-Notch only
Specimen Position	Horizontally	Vertically
Material Tested	Metals only	Plastic and metals
Striking point	Middle of the sample	Upper tip of the sample
Specimen dimension	55x10x10 mm	75x10x10 mm

13.4 Fracture types



13.5 Absorbed Energy - Temperature Graph



13.6 BCC brittle behavior at low temperatures

13.6.1 Cottrell Atmospheres

- Packing efficiency: in α-iron with BCC structure, the octahedral sites for interstitial atoms (e.g. carbon, nitrogen) are much smaller than in γ-iron with an FCC structure
- C solubility and diffusivity higher in BCC: small intestitial atoms, especially carbon, preferentially diffuse into the stress fields around dislocation lines, where more space is available
- This leads to the formation of Cottrell atmospheres, which lock dislocations by clustering interstitial atoms around them

13.6.2 Dislocation pinning

- Cottrell atmospheres cause a pronounced upper yield point $\mathrm{R_{eH}}$ in tensile tests of many BCC metals
- They are also responsible for the brittle fracture behavior of BCC metals at low temperatures, as revealed by the notch impact test
- For plastic deformation to occur, dislocations must first break away from the Cottrell atmospheres
- Hardening a metal reduces its ductility, since the molecules cannot slip freely anymore, causing brittleness
- At low temperatures or high strain rates, this release is particularly difficult, leading to dislocation pinning and increased brittleness

13.7 Absorbed Notch Impact Energy

The absorbed notch impact energy indicates a material's resistance to brittle fracture and is widely used to compare the toughness of structural steels and quenched-and-tempered (Q+T) steels:

Test temperature in °C	**Absorbed Notch Impact Energy $\geq$ 27 J**	**Absorbed Notch Impact Energy $\geq$ 40 J**	**Absorbed Notch Impact Energy $\geq$ 60 J**
20	JR	KR	LR
0	JO	KO	LO
-20	J2	K2	L2
-30	J3	K3	L3
-40	J4	K4	L4
-50	J5	K5	L5
-60	J6	K6	L6

Example: S235JO → S: Steel, 235: R_m, JO: at 0°C

13.8 Summary of Notch Impact Test

13.8.1 Factors promoting brittle fracture

- **Notches**: Create multiaxial stress states that favor brittle failure
- **Sudden loading**: Allows little or no time for plastic deformation

13.8.2 Qualitative assessment of fracture behavior

- Differentiation between **ductile** and **brittle** failure based on absorbed impact of energy and fracture surface appearance
- **BCC metals**: show a clear transition from ductile failure at high temperatures to brittle failure at low temperatures

13.8.3 Applications of the test

- Estabilishing **quality classes** and **ranking structural steels and pressure vessel steels**
- **Quality control** after heat treatments

Part V

Aluminum - Wrought & Cast Alloys

Opening exercise - Name 5 properties and 5 application of aluminum alloys

Property	Application
Heat conductivity	Heat exchangers
Electrical conductivity	High voltage lines
Corrosion resistance ($<$ 10 pH only)	Electronic appliance housing, architecture
Non-magnetic	Electronic appliance housing
Light-weight	Aerospace, automotive industry

14 Introduction

Not relevant for the exam

14.1 Background information about aluminum

- Relatively young metal, discovered about 100 years ago
- More expensive than steel
- Density $\rho = 2.7$ g/cm^3
- Highly malleable (FCC structure)
- Electrical conductivity: 37.7 S·m/mm^2
- Young's modulus E: 70 GPa (lower than steel)
- Melting point: 660°C (lower for cast alloys)
- Naturally passivated: resistant to water and weather within pH 4.5 – 8.5
- Food-safe
- Poor corrosion resistance at pH $>$10 (alkaline environments such as dishwasher or concrete water)
- Oversaturated 5xxx alloys and high-strength 2xxx and 7xxx alloys are prone to corrosion

14.2 Aluminum production

14.2.1 Bayer process

- Bauxite is crushed and dissolved in hot sodium hydroxide
- Aluminum hydroxide ($Al(OH)_3$) precipitates from the solution
- It is then calcinated (heated) to remove water, producing alumina (Al_2O_3)

14.2.2 Smelting flux electrolysis (Hall-Héroult process)

- Alumina is dissolved in molten cryolite
- Al electric current passes through, reducing Al^{3+} to liquid aluminum at the cathode and releasing O_2 at the carbon anode

15 Designation of alloys and conditional designations

15.1 Numerical Designation System (DIN EN 573-1)

EN AW-: Wrought alloys				
Nr.	Main alloying elements	Strain-hardened	Age-hardened	Type of hardening
1XXX	none, >99% Al	Yes (H)	No	Solid-solution hardened Cold-work hardened Fine-grain hardened
3XXX	Mn			
4XXX	Si			
5XXX	Mg, (>3% corrosion)			
2XXX	Cu	in part	Yes (T)	Precipitation hardened
6XXX	Mg + Si			
7XXX	Zn + Mg (+Cu, . . .)			
8XXX	others (Li, Sc, Fe)			

EN AW-: Cast alloys	
Nr.	Main alloying elements
1XXX0	>99% Al
2XXX0	Cu
4XXX0	**Si**
5XXX0	Mg
7XXX0	Zn
8XXX0	Sn
9XXX0	pre-alloys

15.2 Condition Designation (DIN EN 515)

Letter	Meaning
F	Without post-treatment / as fabricated (e.g. cast)
O	Annealed
H	**Strain hardenend**
T	**Thermally treated**

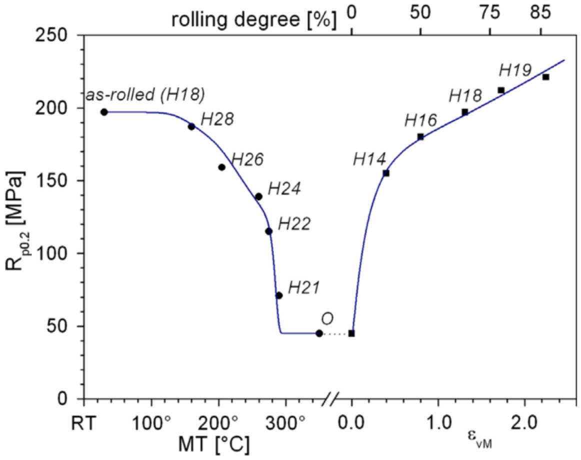
Hxx	Meaning
Hx1	1/8-hard
Hx2	1/4-hard
Hx4	1/2-hard
Hx6	3/4-hard
Hx8	hard
Hx9	extra hard (Hx8 + 14 MPa)

W	solution annealed	+ quenched	(unstable)	
T1	hot-formed	+ quenched		+ naturally aged
T2	hot-formed	+ quenched	+ cold-formed	+ naturally aged
T3	**solution annealed**	**+ quenched**	**+ cold-formed**	**+ naturally aged**
T4	**solution annealed**	**+ quenched**		**+ naturally aged**
T5	hot-formed	+ quenched		+ artificially aged
T6	**solution annealed**	**+ quenched**		**+ artificially aged**
T7	**solution annealed**	**+ quenched**		**+ over-aged**
T8	**solution annealed**	**+ quenched**	**+ cold-formed**	**+ artificially aged**

15.3 Cold-working H

In Hxn, where $n = [1, 9]$, x:

x	Meaning
x=1	cold-worked
x=2	cold-worked and partially annealed for improved temperature resistance
x=3	cold-worked and stabilization-annealed to prevent aging at room temperature
x=4	cold-worked and varnished + blacked



15.4 Precipitation hardening (Age hardening)

15.4.1 Age hardening steps

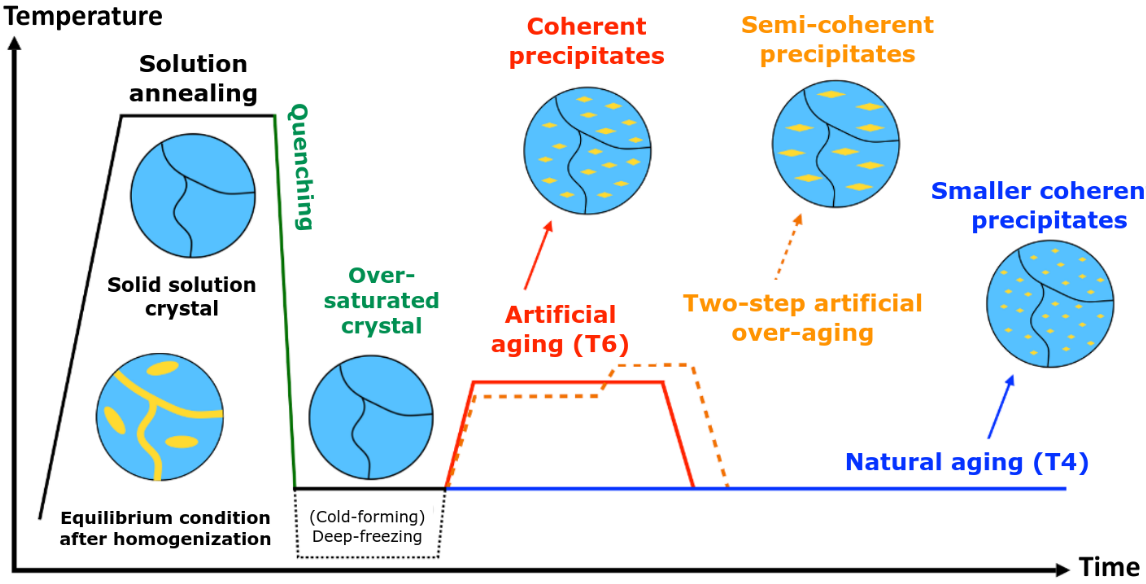
1. **Solution annealing (W)**: dissolves existing precipitates in the alloy
2. **Quenching**: rapidly cools to form a supersaturated solid solution without precipitates
3. **Aging**: small, coherent precipitates form, strengthening the alloy

15.4.2 Aging types

Type	Temperature	Properties
Natural aging	Room temperature	Moderate strength, lower hardness, higher ductility
Artificial aging	Elevated temperature (120-200°C)	higher strength and hardness, lower ductility

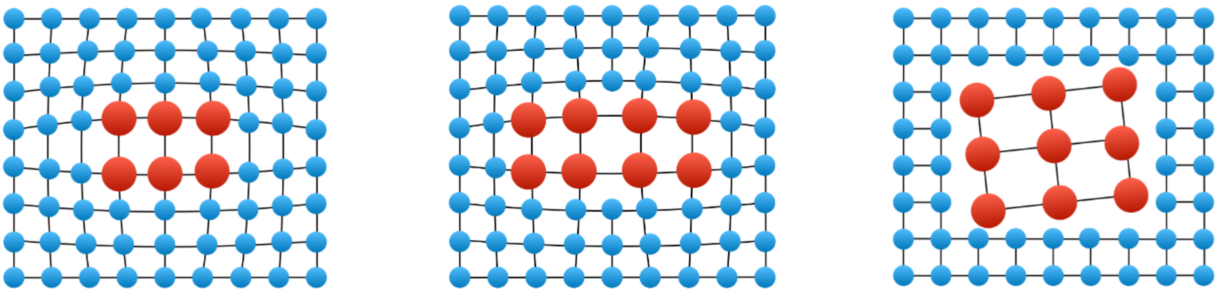
15.4.3 Graph representation

T1 to T8 process paths are visible in section 14.2, table 14.2.3.



15.5 Lattice coherency of precipitates

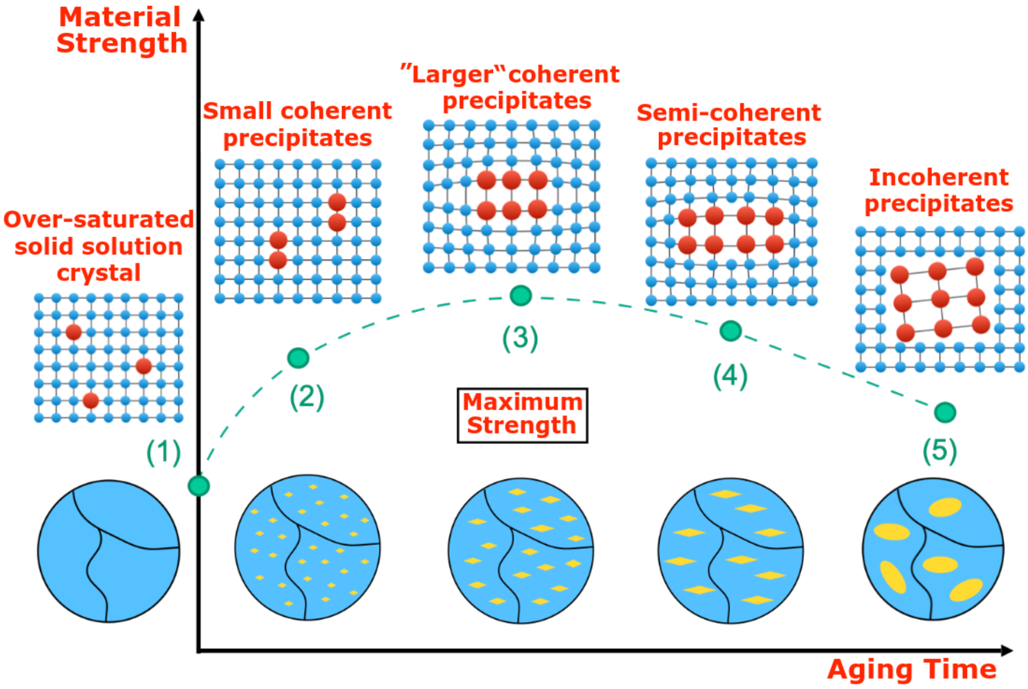
- **Coherent precipitates**: Lattice planes align perfectly, and elastic distortions extend deep into the surrounding crystal. These distortions act as strong barriers to dislocation movement, resulting in a significant increase in strength
- **Semi-coherent precipitates**: Partial lattice mismatch causes dislocations at the interface, reducing elastic distortion and strength compared to coherent precipitates
- **Incoherent precipitates**: Lattice planes are misaligned and incompatible with the matrix, producting little to no elastic distortion and minimal strengthening effect



Coherent (left), Semi-coherent (middle), Incoherent (right)

15.6 Precipitation hardening: Artificial aging

Material strength rises with the formation of coherent precipitates and reaches its maximum when tey are finely dispesed. Over-aging leads to loss of coherency and reduced strength.



Artificial aging of EN AW-2024 (similar to 6000 and 7000 alloys)

15.7 Precipitates in aluminum alloys

- Precipitates are plate- or disc-shaped, observable under transmission electron microscopy (TEM)
- Coherent GPII zones are metastable and maintain lattice alignment with the matrix
- Fully stable precipitates become larger and incoherent, leading to over-aging and reduced strength

15.7.1 Precipitation hardening in Aerospace

Process overview of a sheet metal ribs in the horizontal stabilizer of the PC-12 aircraft (EN AW-2024/AlCu4Mg1)

1. Solution annealing and quenching: material becomes soft
2. (Optional) Deep freezing for storage or transport to prevent premature aging
3. Cold forming using a hydrostatic press with a single-piece die
4. Natural aging at room temperature for approximately 4-5 days, final condition: EN AW-2024-T42
5. Surface treatment: chromating, priming, and painting.

16 Aluminum Wrought Alloys

16.1 Pure Aluminum

16.1.1 Properties

- **Excellent electrical conductivity**. Altough precious metals such as silver, gold, and copper conduct better, aluminum offers superior conductivity when considering both weight and cost
- **High thermal conductivity**, making it ideal for heat dissipation applications
- **Good corrosion resistance**, along with excellent formability and weldability
- **Low inherent strength**, but can be strengthened through cold working and grain refinement
- Certain grades are **highly suitable for surface finishing**, including chemical and electrolytic polishing and anodizing

16.1.2 Applications

- Electrical engineering and electronics: used in power rails, bonding wires, conductive inks, and overhead high-voltage cables (often with a steel core for added strength)
- Heat exchangers and heat sinks: utilized for efficient heat transfer; when in contact with copper, aluminum should be replaced with stainless steel to prevent galvanic corrosion
- Corrosion-resistant cladding: applied as a protective lazer on high-strength aluminum sheets to improve corrosion resistance, commonly used in aircraft and automotive structures
- Food industriy: used for foils (EN AW-1100), dishes, and coffee capsules due to excellent **formability, weldability, gas and odor tightness, and food safety**

16.2 Wrought Alloys: System Al-Mn, (Al-Si)

16.2.1 EN AW-3XXX

- Strengthened by **solid-solution** and **cold-work hardening**
- **Stronger than pure aluminum**, yet remains easy to form, weld, and offers good corrosion resistance
- **Typical applications**: chemical and storage tanks, kitchen and cooking equipment, heat exchangers and conductors (EN AW-3003), gas pipes, architectural components, and beverage can bodies (EN AW-3004)

16.2.2 (EN AW-4XXX)

- Strengthened by **solid-solution** and **cold-work hardening**
- Used mainly as **cast alloys** and **corrosion-resistant coatings**, such as EN AC-44200 (Al-Si12 eutectic alloy)
- Commonly applied in 4XXX welding wires due to their low eutectic melting point

16.3 Wrought Alloys: System Al-Mg

16.3.1 EN AW-5XXX

- Strengtened by **solid-solution** and **cold-work hardening**
- **Stronger than 3000-series alloy**
- Excellent **weldability** and **corrosion resistance**
- At higher magnesium content, incoherent precipitates form, making these alloys **unsuitable** for age hardening
- Unlike high-strength precipitation-hardened aluminum alloys, strength loss in weld zones is minimal if the alloy is not supersaturated
- **Typical applications**: Used for road signs, household appliances, ship components, cookware, food processing equipment, hydraulic lines, and fuel tanks (EN AW-5052). Also applied in beverage can lids (EN AW-5182), pressure vessels, truck and trailed bodies, ship hulls,rocket parts, and railway wagons (EN

AW-5083). In aircraft contruction, alloys such as EN AW-5052 and EN AW-5086 in cold-worked (HXX) condition are used for sheets and pipes

16.4 High-Strength Wrought Alloys

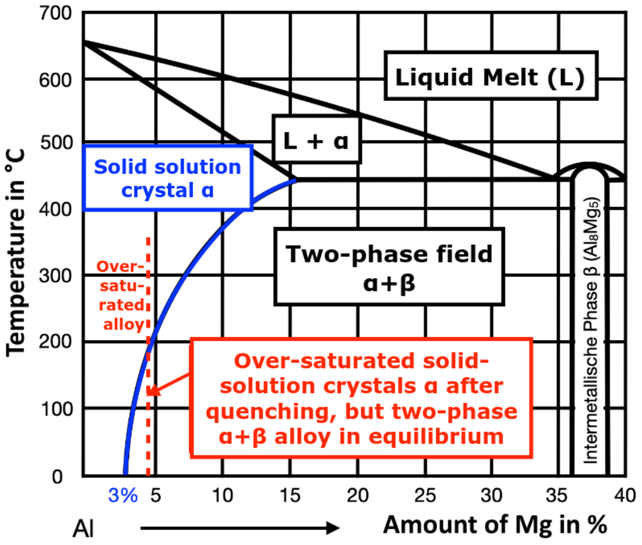
16.4.1 For lightweight construction

- Over-saturated (and work-hardened) 5XXX Al-Mg alloys with more than 3% Mg
- Precipitation-hardened alloys (sometimes combined with cold-work hardening):
  6XXX (Al-Mg-Si), 2XXX (Al-Cu), 7XXX (Al-Zn-Mg), (*8XXX and special alloys, e.g. Al-Li, Al-Sc, Al-Fe*)

16.4.2 Over-Saturated 5XXX

Risk of Intercrystalline Corrosion (IC) and Stress Corrosion Cracking (SCC)!

- Alloys with $< 3\%$ Mg form a **single-phase α solid solution** of aluminum at room temperature
- Alloys with $> 3\%$ Mg remain **homogeneous only after quenching**, forming a **super-saturated α solid solution**
- When exposed to temperature between 60°C and 200°C, these alloys revert to a **stable two-phase $\alpha+\beta$ structure**
- The **β intermetallic phase** (Al_8Mg_5) forms mainly along grain bonundaries, making the material **susceptible to IC and SCC**



Real example of Super-Saturated 5XXX Rods

- Minimal surface corrosion in salt water below 60°C
- Over-saturated 5XXX alloys: Comparable strength to 6XXX-T6 (without T6 treatment), but prone to SCC and IC in chloride environments above 60° (e.g. sunlight exposure). The **β-phase** at grain boudaries promotes corrosion; H3x stabilization is effective only up to 80°C
- Arid coastal climates: sald-laden winds and daily humidity cycles cause condensation and evaporation, increasing corrosion risk
- <3% Mg alloys: no SCC, but low strength, requiring heavy cold working, which itself raises corrosion susceptibility

Compairson with 6XXX-T6:

- Achieves similar strength as over-saturated (and cold-worked) 5XXX alloys, with no SCC risk
- Can still experience IC if Cu $> 0.1\%$

16.5 Precipitation-Hardenable Alloys: System Al-Mg-Si

Al-Mg-Si systems are suitable for everyday use

16.5.1 EN AW-6XXX

- **Precipitation hardening**: main alloying elements are magnesium and silicon
- **Balanced performance**: excellent combination of strength and technological properties, including **formability, weldability, anodizability, machinability, and corrosion resistance**
- **Typical applications**:
  - **EN AW-6061**: bicycle and e-bike frames, tank wagons, and X-ray beam shaper parts
  - **EN AW-6062**: aerospace interion components, extruded profiles, cranes, and ore containers
  - **EN AW-6063**: architectural elements, doors, windows, consumer products (smatphones/laptop housings), and shop interiors
- **EN AW-6026 and EN AW-6012**: offer **excellent machinability**, sometimes achieved by adding small amounts of lead
- **EN AW-6101**: used for mechanically stable electrical conductors

16.6 High-Strength Wrought Alloys: System Al-Cu

16.6.1 EN AW-2XXX

EN AW-2024 is the most important alloy for aircraft sheets

- Naturally aged (T3, T4): high fatigue strength
- Artificially aged (T6): high static strength
- **Poor weldability** (by melting), therefore **friction stir welding (FSW)** or **laser welding** is preferred
- **Prone to corrosion**. Corrosion protection: Chromatization (CCC), primer, Dinitrol
- Due to over-aging, hardened aluminum alloys generally **cannot be used above 100-180°C**
- EN AW-2124-T851, CCC, Primem, PUR: Solution annealing, water quenching, stress relief by controlled stretching, forming, and natural aging.

16.7 High-Strength Wrought Alloys: System Al-Zn-Mg

16.7.1 EN AW-7XXX

- **Precipitation-hardened**: main alloying elements are **zinc, magnesium, (copper)**
- **Artificially aged**: **very hard strength**, but **poor corrosion resistance** and **not weldable by melting** (FSW is preferred due to lower heat and reduced heat-affected zones)
- Typical applications:
  - **EN AW-7005**: laptop and smartphone housings, baseball and golf clubs
  - **EN AW-7010**: climbing carabiners
  - **EN AW-7050**: upper wings and structural parts in commercial aircraft
  - **EN AW-7075**: aerospace components, ski poles, and other high-strength structures

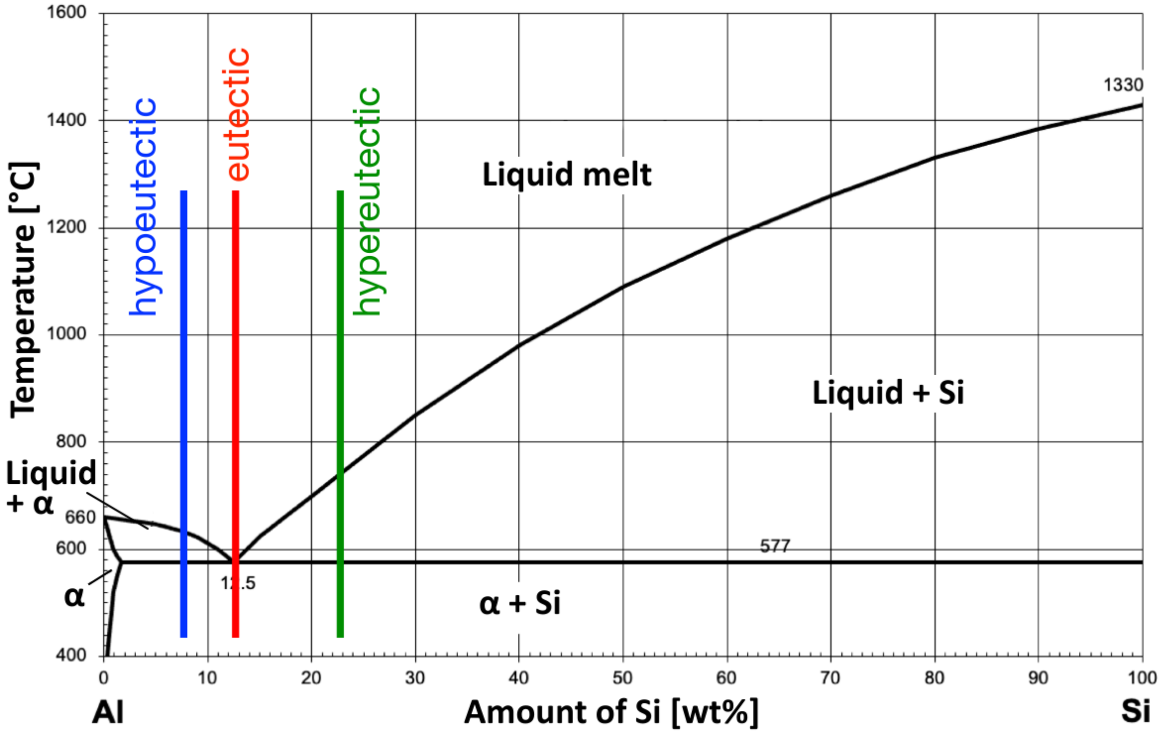
Risk of stress corrosion cracking (SCC) and exfoliation corrosion:

- **Artificial aging, slightly over-aged (T7)**: typically 12-24h at 120°C (formation of coherent precipitates), followed by 4-6h at 175°C (conversion to semi-coherent precipitates), reducing lattice distortion and internal stress
- **T6 and T8** are used for non-corrosive environments (no oxygen or moisture) or short service life application (e.g. racing)
- **Maximum strength** due to coherent precipitates

16.8 Mechanical Properties Overview

Short name (Numerical)	Short name (Chemical)	Condition	$R_{p0.2}$ (MPa)	R_m (MPa)	A (%)
EN AW-1100	EN AW-Al99.0Cu	○	35	90	40
		H19	**160**	**180**	**1**
EN AW-3004	EN AW-AlMn1Mg1	○	60	200	16
		H18	**230**	**260**	**2**
EN AW-5083	EN AW-AlMg4.5Mn0.7	F	110	270	10
		H14	**280**	**400**	**3**
EN AW-2024	EN AW-AlCu4Mg1	○	140	220	13
		T4	**275**	**425**	**14**
		T6	315	425	4
		T8	400	455	3
EN AW-6061	EN AW-AlMg1SiCu	○	55	125	25
		T4	145	240	22
		T6	**275**	**310**	**12**
EN AW-6082	EN AW-AlSi1MgMn	○	110	160	12
		T4	110	205	12
		T6	**260**	**310**	**8**
EN AW-7075	EN AW-AlZn5.5MgCu	○	165	275	8
		T6	**500**	**560**	**7**
EN AW-2195	EN AW-AlCu4Li1	**T8**	**548**	**586**	**8**

17 Aluminum Cast Alloys



Al-Si phase diagram showing hypoeutectic, eutectic, and hypereutectic regions

17.1 Eutectic Cast Alloys

17.1.1 Properties

- **Easy to cast**: lowest melting temperature with a distinct melting point (no melting range)
- Excellent flow behavior and low viscosity
- Molds fill easily, allowing fine and detailed structures to be cast
- Adding sodium (Na) or strontium (Sr) refined the eutectic structure and slightly shifts the eutectic point to higher silicon contents (13-14%)
- Adding titanium (Ti) or titanium boride (TiB_2) prevents the formation of undesirable silicon needles or plates in the eutectic microstructure

17.1.2 Typical alloys

- **EN AC-44100** and **EN AC-44200** (both designed as EN AC-AlSi12) have a good corrosion resistance
- **EN AC-44300** (EN AC-AlSi12(Fe)) contains approx. 1% Fe
- **EN AC-47000** (EN AC-AlSi12(Cu)) contains approx. 1% Cu

17.1.3 Typical applications

- Engine and pump housing, ribbed and thin-walled components, cylinder blocks and heads (upper part of the engine block)
- Hot-dip coatings for steel, providing corrosion protections

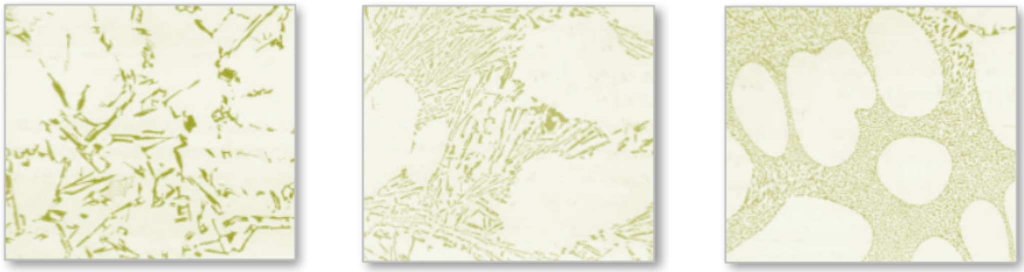
17.2 Hypoeutectic Cast Alloys

17.2.1 Properties

- Crystallization occurs within the two-phase region: liquid melt plus primary aluminum solid-solution crystals
- Microstructure at room temperature: primary aluminum solid-solution crystals with residual eutectic
- Samm additions of Mg, Cu, or Fe enable effective precipitation hardening of the primary aluminum solid-solution phase

17.2.2 Applications

- Electric vehicle engine housing made of EN AC-46500 (EN AC-AlSi8Cu3)
- Electric vehicle chassis components made EN AC-42000 (EN AC-AlSi8Mg) and EN AC-43500 (EN AC-AlSi10MgMn)



Coarse-grained eut. (Left), Lamellar needle-like eut. (Middle), Refined fine-grained eut. Sr/Na (Right)

17.3 Hypereutectic Cast Alloys

17.3.1 Properties

- Contain up to ≈ 25% silicon (Si)
- **Primary silicon crystal** provide excellent wear resistance even at high temperatures and reduce thermal expansion

17.3.2 Applications

- Used in pistons for combustion engines (**piston alloys**)
- **EN AC-48000**: used for pistons in automotive engines, offers **high wear resistance and high strength** in the artificially aged T6 condition ($R_{p0.2} \approx 240$MPa, $R_m \approx 280$MPa)

17.3.3 Recent developments

- In improved, near-eutectic Al-Si alloys, the formation of primary silicon crystals can be promoted by adding small amounts of aluminum phosphide as a nucleating agent
- Primary Si crystals form, for instance, in the the near-eutectic alloy **EN AC-48000 (EN AC-AlSi12CuNiMg)**, which containg 10-13.5% Si, about 1% Cu, Mg, and Ni.

17.4 Cast alloys recap

Comparison of hypoeutectic, eutectic, and hypereutectic Al-Si cast alloys

Alloy type	**Main features**	**Advantages**	**Disadvantages**
Hypoeutectic	Al-rich (< 12% Si)	Good castability Good ductility Precipitation hardenable (Mg, Cu, Fe) Easy to machine	Lower wear resistance Higher thermal expansion
Eutectic	Eutectic composition Approx. 12% Si	Excellent fluidity and castability Fine structure, easy mold filling Good corrosion resistance	Moderate mechanical strength Can be brittle if unmodified
Hypereutectic	Si-rich (12% – 25%)	Very high wear resistance Low thermal expansion Good dimensional stability at high T	Poor ductility Hard to machine Difficult to cast (segregation)

In summary:

- **Hypoeutectic alloys**: best mechanical balance and toughness
- **Eutectic alloys**: best castability and corrosion resistance
- **Hypereutectic alloys**: best wear resistance and thermal stability

18 Surface technology - corrosion protection

18.1 Natural Oxide Layer on Aluminum

- Aluminum has a strong affinity for oxygen, leading to the **immediate formation of a natural, compact layer of Al_2O_3**. This oxide layer is:
  - **Ceramic and very hard**
  - **Corrosion-resistant**, as it is already oxidized (passivated)
  - **Chemically stable** within a pH range of 5 to 8
  - **Extremely thin**, only a few nanometers thick
- The oxide layer can be strengthened (thickened) by:
  - **Chemical processes** such as chromating, chromitizing, or water boiling
  - **Electrochemical processes** such as anodizing

18.2 Chemical Conversion Coatings

- Removal of the natural oxide layer through **pickling or etching**
- Conversion of aluminum into a layer of metal oxide, chromate, chromite, or phosphate using the corresponding acids
- Produces a **very thin coating** (in the micrometer range, typically 0.1 - 5 g/m^2) that may contain microcracks
- Common brands: Alodine (R), Bonder (R)
- **Chromate Conversion Coating (CCC)** is based on chromium acid (Cr VI):
  - Can be transparent, yellow, or blue
  - Serves as an adhesion layer for primers, varnishes, and paints
  - Future alternatives: Cr(VI)-free systems such as chromiting (Cr III) or chromous acid treatments
- **Phosphating** (phosphoric acid-based):
  - Acts as an adhesive primer for paint or varnish
  - Commonly used in the food industry

18.3 Electrochemical Anodizing

18.3.1 GS process

Uses direct current (DC) with sulfuric acid. Produces oxide layers up to 30 μm thick. Mainly **decorative**; color pigments (exchept white) can be introduced into the pores.

18.3.2 GSX process

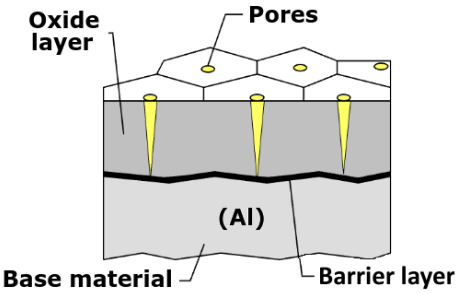
Uses direct current (DC) with sulfuric and oxalic acids. Creates thicker layers up to 80-150 μm, offering **excellent wear protection**.

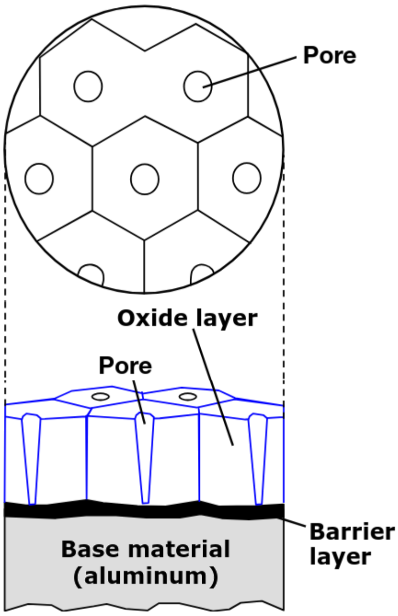
18.3.3 Chromic Acid Anodizing (CAA) process

Produces a **thin, flexible, and low-crack** oxide layer with **very high corrosion resistance**. Used only in **aerospace applications** due to the **carcinogenic Cr(VI)** solutions required.

18.3.4 Tartaric Sulfuric Acid Anoditing (TSA) process

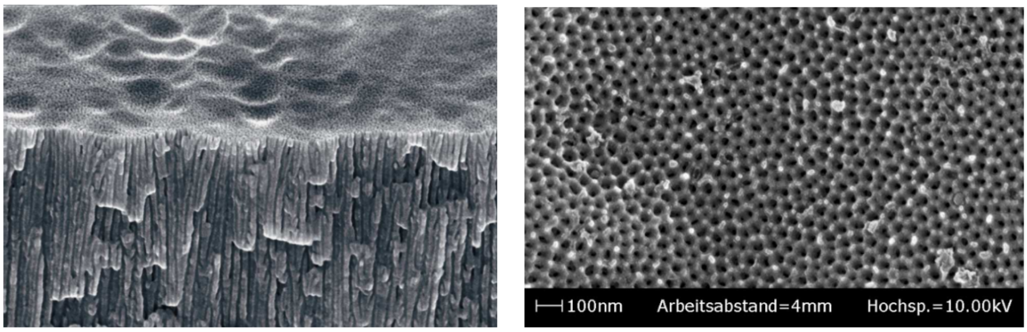
Developed as a **safer and environmentally friendly** alternative to the carcinogenic CAA process.





18.4 Porosity

- The anodized oxide layer is **porous**, consisting of open cylindrical pores extending from the surface down to a thin, dense **barrier layer**
- These **open pores** can absorb dyes, lubricants, or sealing agents to improve appearance, wear resistance, and corrosion protection
- After sealing (by hydration or chemical treatment), the pores become **closed**, preventing further penetration of contaminants or moisture
- The controlled porosity is a key feature that makes anodized aluminum both functional and decorative



Closed pores (Left), Open pores (Right)

18.5 High-Strength Aluminum Alloys in Aviation

Corrosion protection using a simple oxide layes is often insufficient:

- High-strength aluminum alloys (2XXX, 7XXX) offer **poor corrosion resistance** when protected only by natural oxide layers or standard anodizing
- **Multi-step surface treatment** is required:
  - **Cleaning** (pickling or etching) to remove impurities and the natural oxide film
  - **Chromating or anodizing with Cr(VI)** (CCC or CAA): still permitted in aerospace applications, although **TSA** is preferred for health and environmental reasons
  - **Primer**: a diluted **epoxy coating**, typically green-yellow in color due to Cr(VI)
  - **Varnish/paint**: **polyurethane (PUR)** finish for enhanced protection and durability
- Alloys of the 6XXX, 5XXX, 3XXX, and 1XXX series are **well-suited for GS anodizing** and are sometimes finished with **paint coating** for additional protection

18.6 Recent alternatives (REACH, RoHS)

18.6.1 CAA replacement

CAA is being replaced by TSA. The consequences of using TSA are many:

- **Slightly reduced fatigue strength** and somewhat **lower corrosion resistance**
- Requires **shorter maintenance intervals** due to increased risk of **fatigue crack** and **corrosion damage**

18.6.2 Chromating alternatives

Instead of Cr(VI) and chromic acid, **chromitizing with Cr(III)** (chromous acid) is used

18.6.3 Primer alternatives

Experiments are ongoing with **Li- and Zn-based primers** to replace Cr(VI) compounds

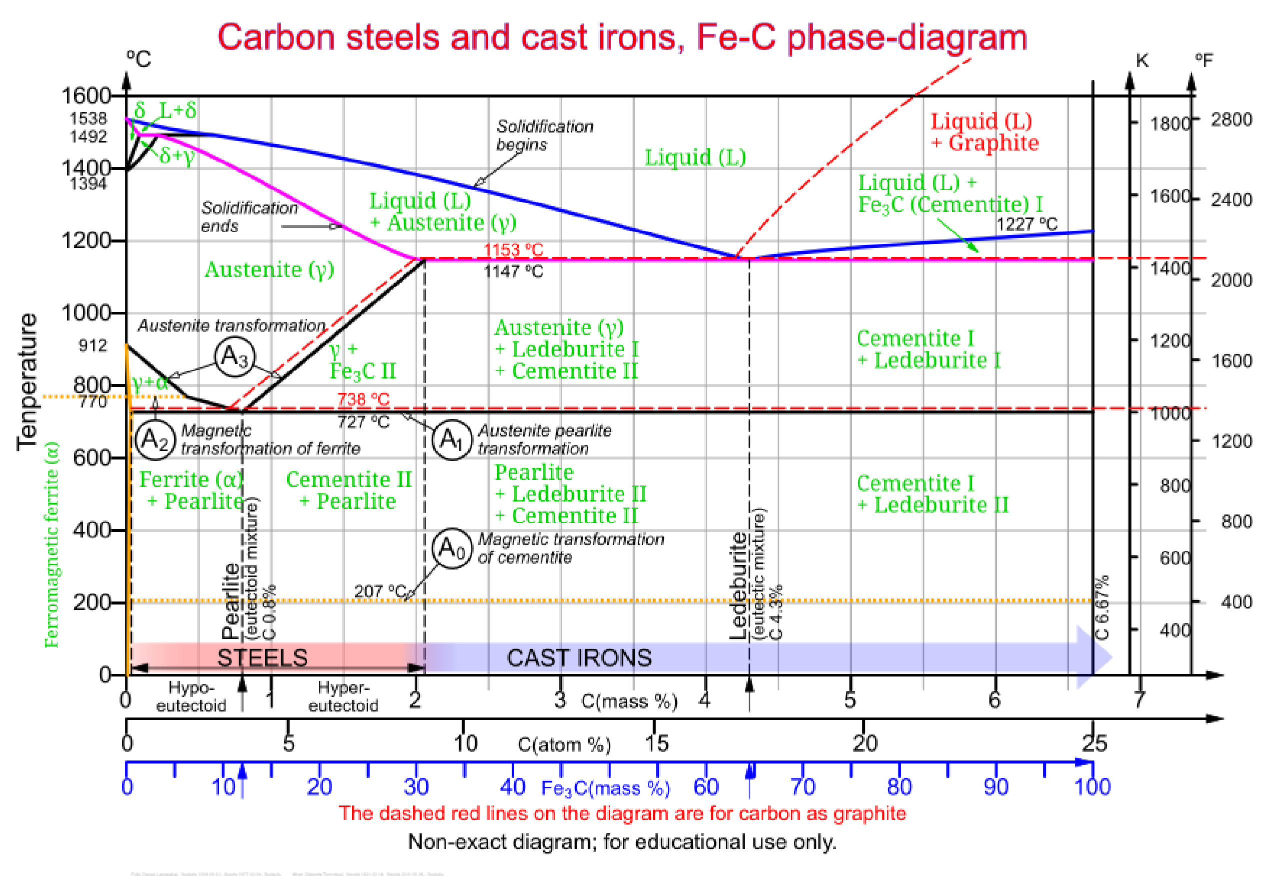
18.6.4 Cadmium (Cd) replacements

On precipitation-hardened steels such as bolts and screws, **Zn-Ni galvanic coatings** are now applied instead of cadmium plating

Part VI

Metallography and Microscopy

19 Steel Microstructure



Fe-C phase diagram

19.0.1 Hypoeutectoid Steel L$_1$

19.0.2 Eutectoid Steel L$_2$

19.0.3 Hypereutectoid Steel L$_3$

19.1 Faster Cooling and Quenching

19.2 Martensite

19.3 Bainite

19.4 Martensitic Hardening vs. Q+T Treatment

20 Metallographic microstructure analysis

20.1 Crystallographic Structure

Part VII

Measurement of chemical compositions

21 Selected methods

21.1 X-ray Fluorescence (XRF)

21.2 Optical Emission Spectrometry (OES)

21.3 Energy-dispersive spectroscopy (EDS, EDX, EDAX)

21.3.1 Line Scan EDS

21.3.2 EDS Area Scan

21.4 Infrared Spectroscopy for Polymers (FTIR)

A Glossary

Alloy A mixture of two or more elements, where at least one element is a metal.

Amorphous Non-crystalline material with no long-range order.

Anisotropy Direction-dependent properties of a material (Monocrystalline and polycrystalline with texture)

Annealed A heat treatment process in which a metal is heated and slowly cooled to reduce internal stresses, soften the material, and improve ductility and machinability.

Anodizing Electrochemical process that thickens and stabilizes the natural oxide layer to improve corrosion and wear resistance.

Austenite (γ-Fe) Face-centered cubic (FCC) phase of iron, stable at high temperatures and soluble up to 2% carbon.

Bainite Strong, ductile microstructure formed in steels at temperatures between those that form pearlite and martensite, consisting of a mixture of ferrite and carbides.

Barrier layer Dense sublayer at the base of anodic pores that protects the underlying metal.

Brittle Material that fractures without significant plastic deformation.

Brittleness The tendency of a material to fracture with little to no plastic deformation.

Carbide A compound composed of carbon and a less electronegative element, often forming hard materials used in cutting tools and abrasives.

Carburizing A heat treatment process that enriches the surface layer of a low-carbon steel with carbon to increase its hardness.

Cast The metal has been melted and poured into a mold, where it solidifies into shape without further mechanical working.

Cementite (Fe_3C) A hard, brittle intermetallic compound of iron and carbon, forming part of the microstructure in steels and cast irons.

CHD Case hardening depth. The depth to which a material has been hardened by surface treatment processes.

Chromating Chemical conversion coating forming a thin chromate film for corrosion protection and paint adhesion, traditionally Cr(VI)-based.

Coherent A condition in which the atomic planes of two phases, such as a precipitate and its matrix, are continuous across their interface, resulting in lattice alignment and elastic strain without dislocations.

Corrosion Degradation of a metal by chemical of electrochemical reaction with its environment.

Cottrell atmosphere A cluster of intestitial atmos (e.g. C, N) around a dislocation in BCC metals, causing dislocation pinning and higher yield stresses.

Crude steel Refined steel with $< 2\%$ carbon that has been produced but not yet refined or processed into finished products.

Crystalline Material with atoms arranged in a highly ordered microscopic structure, forming a crystal lattice that extends in all directions.

Dislocation A linear defect in the crystal structure where there is an irregularity in the arrangement of atoms.

Ductility The ability of a material to undergo plastic deformation before fracture.

Eutectic Alloy composition that solidifies at a single, lowest temperature, producing a fine and uniform microstructure.

Fatigue Progressive structural damage caused by repeated or fluctuating stress below the static strength of the material.

Ferrite (α-Fe) Body-centered cubic (BCC) phase of iron, stable at room temperature and low C solubility.

Hardening The process of increasing a material's hardness and strength through various methods such as heat treatment or work hardening.

Hardness Resistance of a material to localized plastic deformation, typically measured by indentation tests.

HCF High-cycle fatigue. It occurs when materials are subjected to stresses much lower than their yield strength, at a high number of cycles.

Heterogeneous Non-uniform composition and properties throughout the material.

Homogeneous Uniform composition and properties throughout the material.

Hypereutectic Alloy with more solute than the eutectic composition. It contains primary Si crystals and eutectic matrix.

Hypoeutectic Alloy with less solute (e.g. Si) than the eutectic composition. It contains primary aluminum crystals and eutectic mixture.

Impact Toughness The ability of a material to absorb energy under sudden loading before fracture.

Isothermal transformation A phase transformation that occurs at a constant temperature.

Isotropy Direction-independent properties of a material (Amorphous)

Ladle A large container used to hold and transport molten metal during steelmaking and casting processes.

LCF Low-cycle fatigue. It happens when materials are subjecter to higher stresses, typically exceeding the yield strength, at a smaller number of cycles.

Martensite A hard, brittle phase formed by the rapid quenching of austenite, characterized by a body-centered tetragonal (BCT) structure.

Mild steel Low-carbon steel with a carbon content of approximately 0.05% to 0.25%, known for its ductility and weldability.

Monocrystalline Material consisting of a single crystal or a continuous crystal lattice with no grain boundaries.

NHD Nitriding hardening depth. The depth to which a material has been hardened by nitriding.

Nitriding A heat treatment process that introduces nitrogen into the surface of a steel to form hard nitrides, enhancing surface hardness and wear resistance.

Oxide layer Protective film of aluminum oxide formed by oxidation or anodizing.

Passivation Process of forming a stable, protective oxide layer that prevents further oxidation or corrosion.

Pearlite A two-phase lamellar microstructure consisting of alternating layers of ferrite and cementite, formed during the slow cooling of austenite.

Phase A region of material that is chemically and structurally uniform.

Phosphating Chemical treatment producing a phosphate layer for paint adhesion and corrosion resistance.

Pig iron High-carbon iron produced in a blast furnace, used as a raw material for making steel and cast iron.

Poisson's ratio ν The ratio of transverse strain to longitudinal strain in a material under uniaxial loading.

Polycrystalline Material composed of many crystallites of varying size and orientation.

Polymorphism / Allotropy Ability of a material to exist in more than one form or crystal structure.

Porosity Open microscopic pores in the oxide layer that can be filled (sealed) with dyes, lubrificants, or inhibitors.

Precipitation hardening Heat-treatment process that strengthens alloys by forming finely dispersed precipitates.

Q+T Quenching and tempering. A heat treatment process that involves rapid cooling (quenching) followed by reheating (tempering) to improve mechanical properties.

Quasi-isotropy Approximate isotropy in polycrystalline materials with random grain orientation (Polycrystalline without texture)

Quenching A rapid cooling process used to harden steel by transforming austenite into martensite.

SHD Surface hardening depth. The depth to which the surface of a material has been hardened.

Shear modulus G The ratio of shear stress to shear strain in the elastic range of a material.

Slip Large displacement of one part of a crystal relative to another part along crystallographic planes and directions.

Stainless steel Corrosion-resistant steel alloy containing a minimum of 10.5% chromium.

Tempering A heat treatment process that reduces brittleness and increases toughness in quenched steels by reheating to a temperature below the eutectoid temperature.

Toughness The ability of a material to absorb energy and plastically deform without fracturing.

TSA Tartaric-Sulfuric Acid Anodizing. Cr(VI)-free anodizing process used in aviation as a safer alternative to CAA (chromic acid anodizing).

Vacancy A point defect in a crystal lattice where an atom is missing from its regular lattice site.

Varnish Transparent protective coating applied to stufaces, typically meltal, wood, or paint, to enhance appearance and provide resistance against corrosion, moisture, and wear.

Wrought The metal has been mechanically worked or shaped (by rolling, forging, or extursion) after solidification, giving it a refined structure and improved mechanical properties compared to cast metals.

Young's modulus E The ratio of normal stress to longitudinal strain in the elastic range of a material.

B Nomenclature

Alloy series

1XXX	Commercially pure aluminum (high conductivity, soft)
2XXX	Al-Cu alloys (high strength, poor corrosion resistance)
3XXX	Al-Mn alloys (good formability, non-heat-treatable)
4XXX	Al-Si alloys (good castability, used in welding)
5XXX	Al-Mg alloys (good weldability and corrosion resistance)
6XXX	Al-Mg-Si alloys (medium strength, excellent formability)
7XXX	Al-Zn-Mg alloys (very high strength, lower corrosion resistance)

Coatings and Surface Treatments

CAA	Chromic Acid Anodizing
CCC	Chromate Conversion Coating
Chromating	Chemical conversion layer of chromates or chromites
Cr(III)	Trivalent chromium (eco-friendly)
Cr(VI)	Hexavalent chromium (toxic, high corrosion resistance)
GS	Sulfuric Acid Anodizing (decorative)
GSX	Sulfuric + Oxalic Acid Anodizing (protective, weat-resistant)
Phosphating	Chemical conversion coating for paint adhesion
PUR	Polyurethane paint or vanish (top protective layer)
TSA	Tartaric-Sulfuric Acid Anodizing (Cr-free, aerospace use)
Zn-NI	Zinc-Nickel galvanic coating for paint adhesion

Ductility measures

A	Fracture strain
A_g	Uniform strain
A_n	Elongation measured with $L_0 = n\sqrt{S_0}$
KV	Notch impact energy, in J, indicator of toughness
Z	Contraction at fracture (elongation at break, in %)

Elastic moduli

E	Young's modulus → 70GPa for aluminum, 210 GPa for steel
G	Shear modulus

Material Characterization Techniques

EDS	Energy-Dispersive Spectroscopy (also EDX, EDAX)
FTIR	Fourier Transform Infrared Spectroscopy
OES	Optical Emission Spectrometry
XRF	X-ray Fluorescence

Ratios

ν	Poisson’s ratio
PREN	Pitting Resistance Equivalent Number = %Cr + 3.3%Mo + 16%N

Strength measures

R_{eH}	Upper yield point
R_{m}	Tensile strength
$R_{\mathrm{p0.2}}$	0.2% yield strength
HB	Brinell hardness
HRC	Rockwell C hardness
HV	Vickers hardness

Transformations and Processes abbreviations

AC	Cast Aluminum
AW	Wrought Aluminum
CHD	Case Hardening Depth
DRI	Direct Reduced Iron
EF	Electric Furnace
EKD	Iron-Iron Carbide Phase Diagram
ESR	Electro Slag Remelting
ETG	Name of the steel grade according to the Swiss standard
FSW	Friction Stir Welding
HAZ	Heat Affected Zone
HSS	High-Speed Steel
IC	Intercrystalline corrosion
L_1	Hypoeutectoid Steel (0.35% C)
L_2	Eutectoid Steel (0.8% C)

L_3	Hypereutectoid Steel (1.4% C)
NHD	Nitriding Hardness Depth
OBC	Oxygen-Blown Converter
OHF	Open Hearth Furnace
PM	Powder Metallurgy
Q+T	Quenching and Tempering
SCC	Stress Corrosion Cracking
SHD	Surface Hardening Depth
VAR	Vacuum Arc Remelting
ZTU/CCT	Continuous Cooling Transformation diagram