

Materials Lab

HSLU, Semester 3

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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

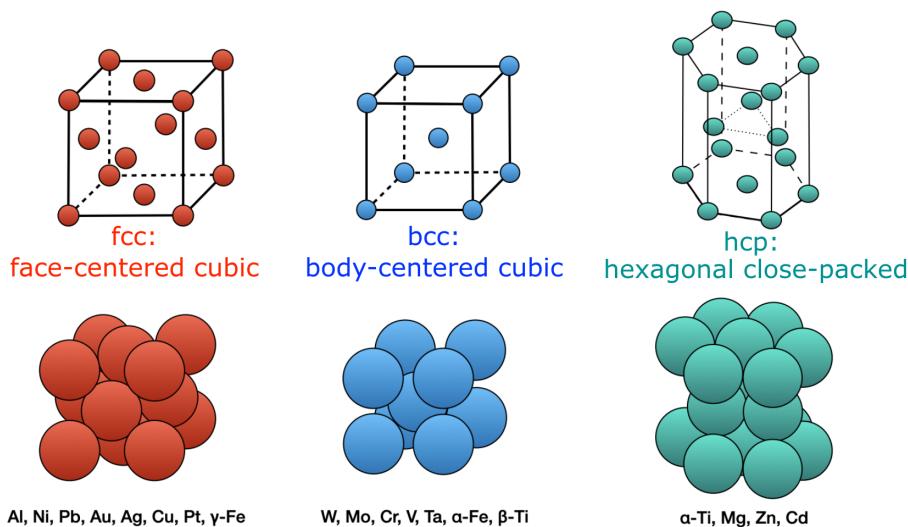
1.1 Material classes and typical properties

Class	4 Typical Properties
Metals / Alloys	1) Conductivity (electric, thermal) 2) Ductility / malleability 3) Castable 4) Shiny (reflective)
Ceramics	1) High temperature resistance 2) Compression resistance 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)

BCC (Body-centered cubic)

HCP (Hexagonal close-packed)

- Packing efficiency:

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

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

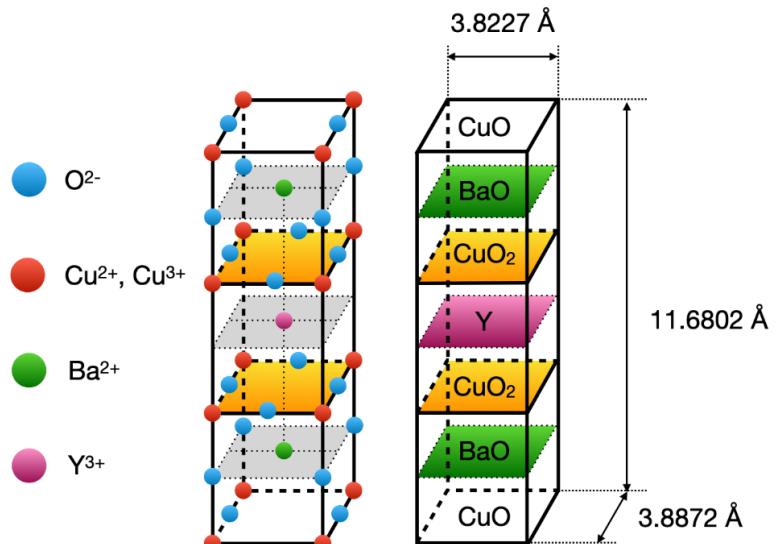
$$\phi = \frac{\pi}{\sqrt{18}} \approx 74\%$$
 - Very few slip systems (3)
 - Closest packed direction

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

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)

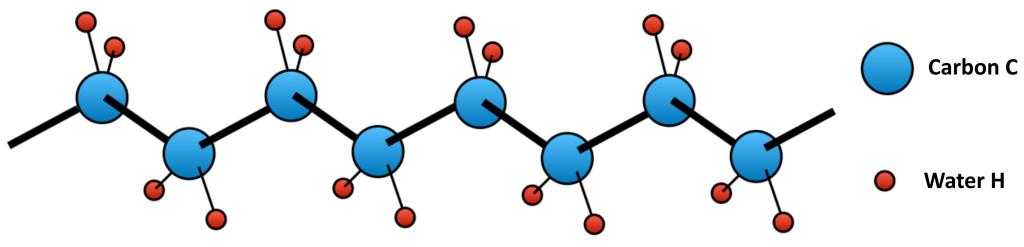


YBCO superconducting ceramic with layered perovskite-like structure

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

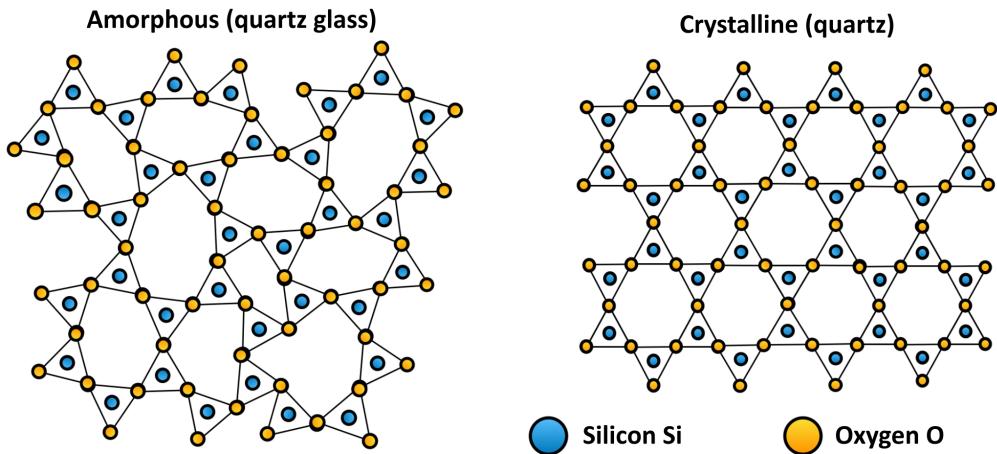
1.5 Amorphous and crystalline materials

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

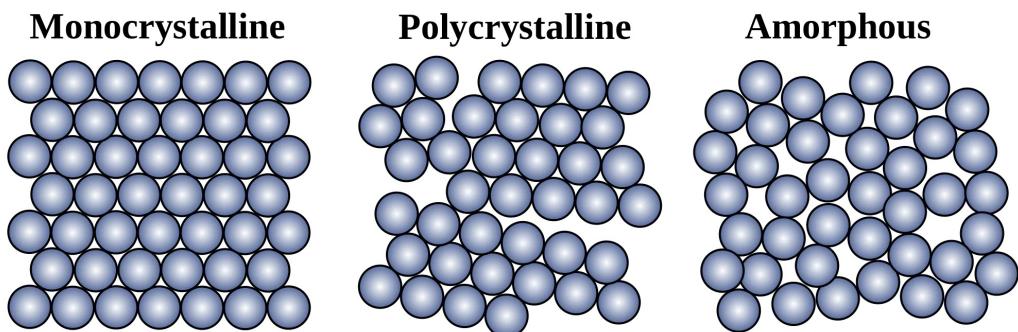
Only for special applications, expensive

- Single-crystal turbine blades ($T > 1000^{\circ}\text{C}$, 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 Directional dependence of the properties of materials

1.6.1 Anisotropy and Isotropy

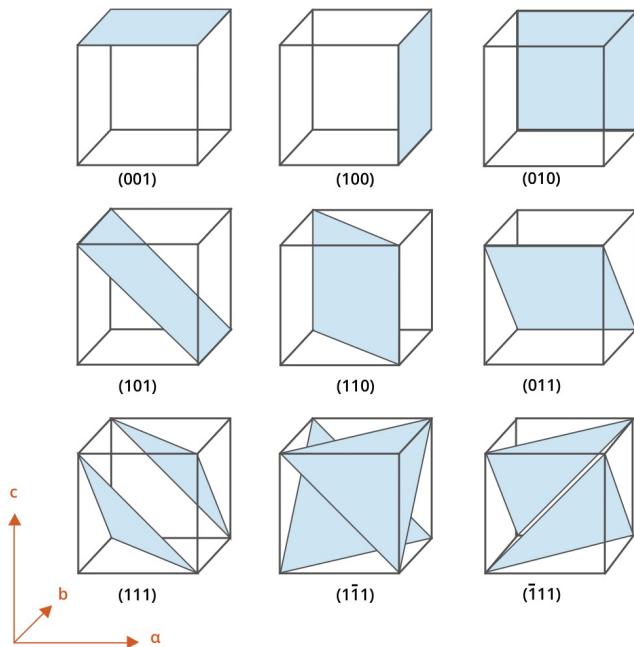
- Anisotropic: Properties depend on direction (e.g. single crystals, wood, composites)
- Isotropic: Properties do not depend on direction (e.g. polycrystalline metals, amorphous materials)

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

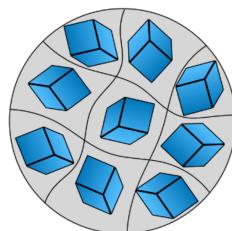
In short, the Miller indices are the reciprocals of the fractional intercepts that the plane makes with the crystallographic axes:



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.

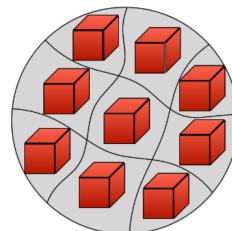


Polycrystalline material without texture

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

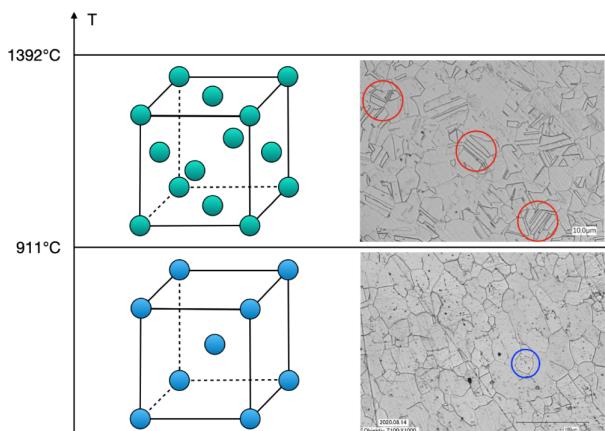
- Isotropic (e.g. glass or amorphous metals)

1.9 Polymorphism (Allotropy)

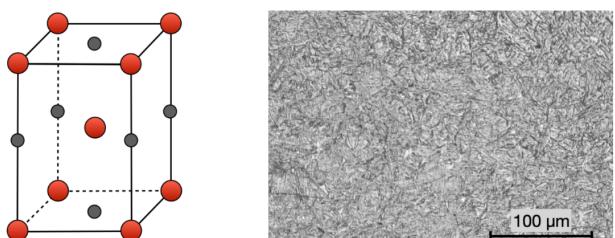
Some materials may exhibit more than one crystal structure:

- Iron $\begin{cases} \alpha\text{-Fe (ferrite, BCC)} & \text{below } 911^\circ\text{C} \\ \gamma\text{-Fe (austenite, FCC)} & 911^\circ\text{C to } 1392^\circ\text{C} \\ \delta\text{-Fe (ferrite, BCC)} & 1392^\circ\text{C to } 1536^\circ\text{C} \end{cases}$
- Titanium $\begin{cases} \text{HCP} & \text{below } 880^\circ\text{C} \\ \text{BCC} & \text{above } 880^\circ\text{C} \end{cases}$
- 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)

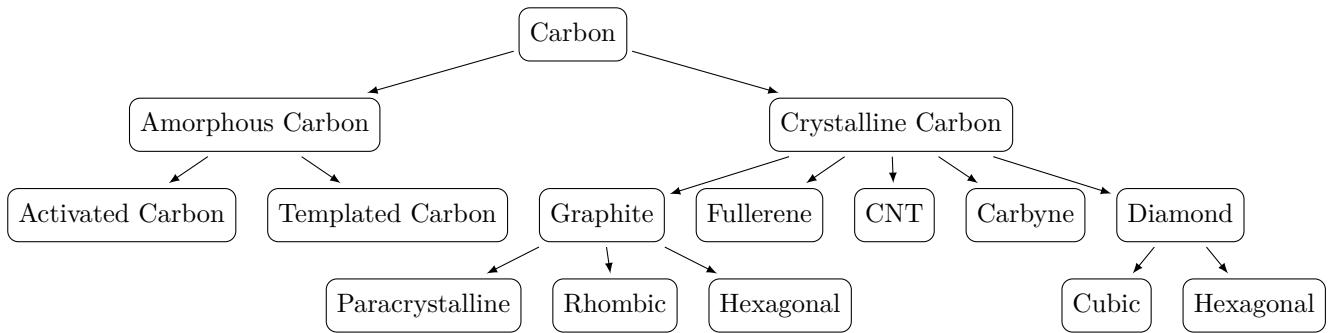


Slow Austenite transformation in steel: Ferrite



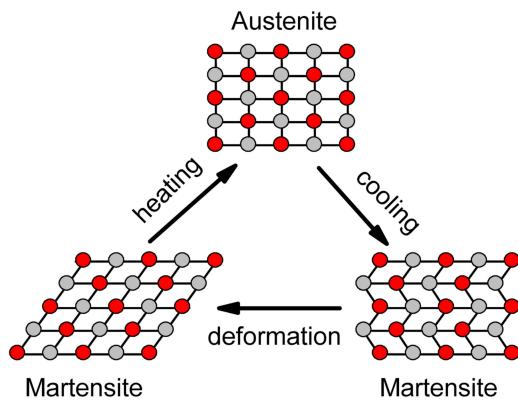
Fast Austenite transformation: Martensite

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:

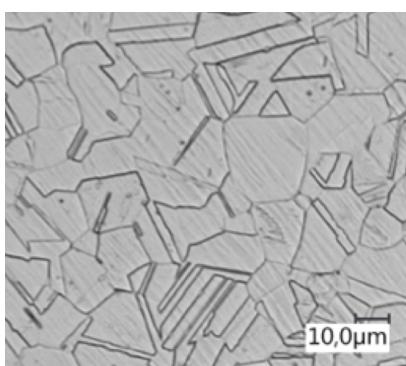
- A phase can be crystalline or amorphous
- At the phase boundaries, a sudden change in structure, properties and chemical composition occurs

Polycrystalline materials can consist of:

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

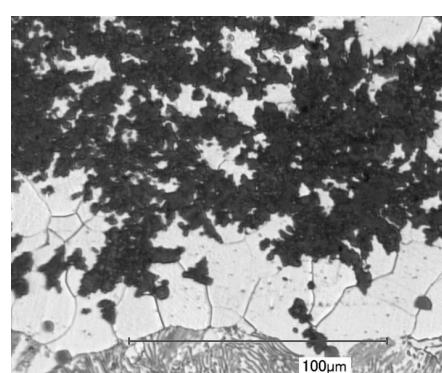
1.10.1 Homogeneous microstructure

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. Ni₃Ti, Fe₃C, ...)
 - (Impurity particles, e.g. added ceramic particles or slag residues)

2 Most important metal structures and crystal lattice defects

2.1 Lattice defects

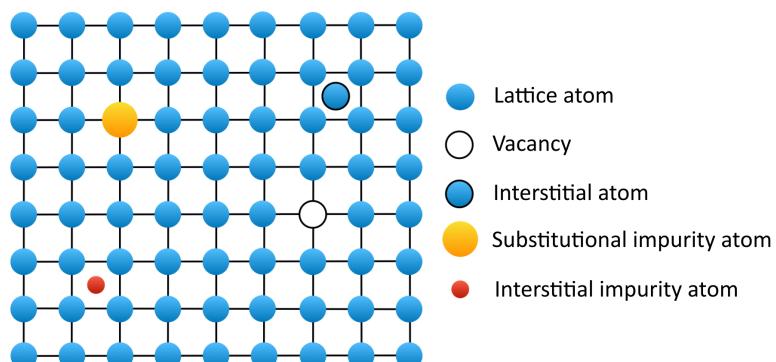
Lattice defects are irregularities in the crystal structure:

- **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.

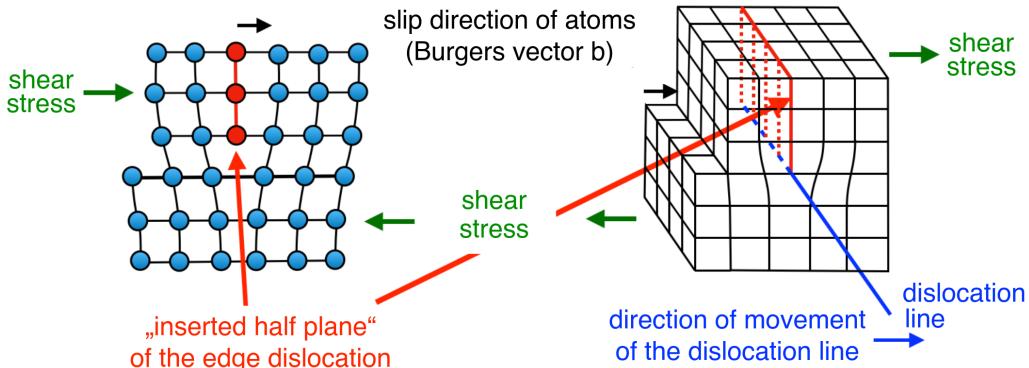


Point defects: vacancy, interstitial atom, substitutional atom

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.



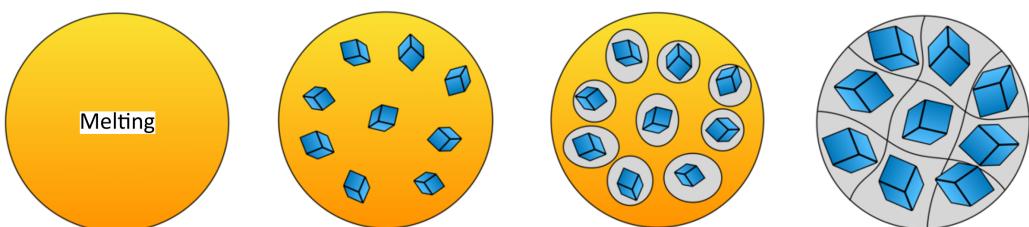
Line defects: edge dislocation, screw dislocation

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 .



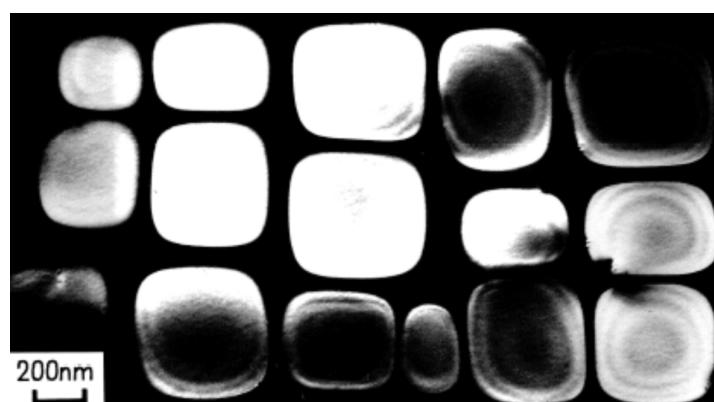
Crystallization from a melt:

(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

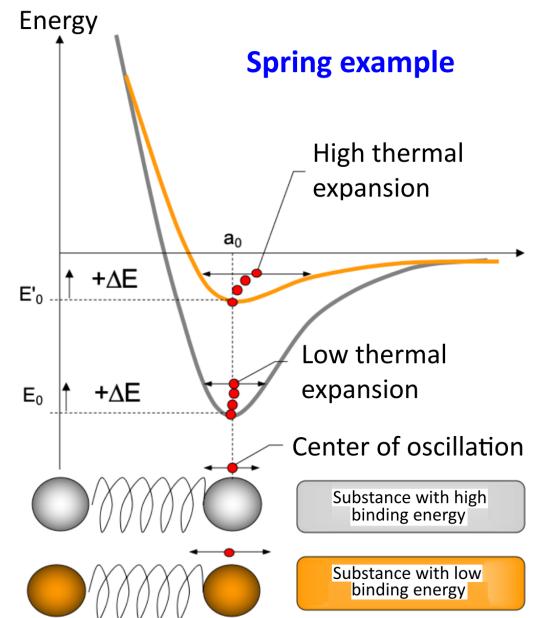
3.1 Elastic deformation

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:

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

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:

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

3.2.3 Relationship between the 3 isotropic elastic constants G

For isotropic materials, the following relationships hold:

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

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.

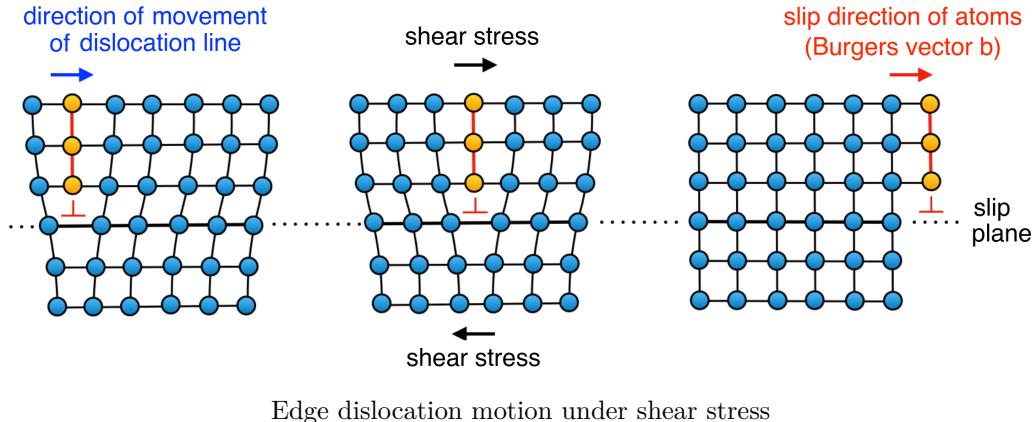
3.4 Dislocation Slip Model

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:

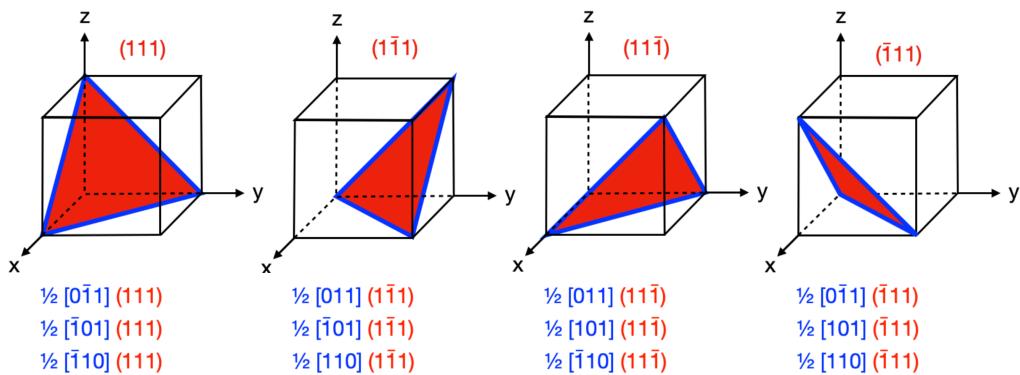
- Inserted half-plane, the end of which forms the dislocation line
- Dislocation moves on densely packed slip planes



3.5 Slip systems

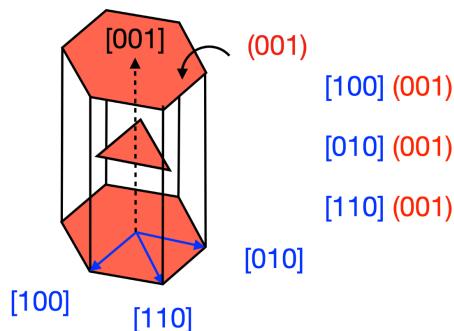
3.5.1 Slip systems in FCC metals (Miller indices)

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



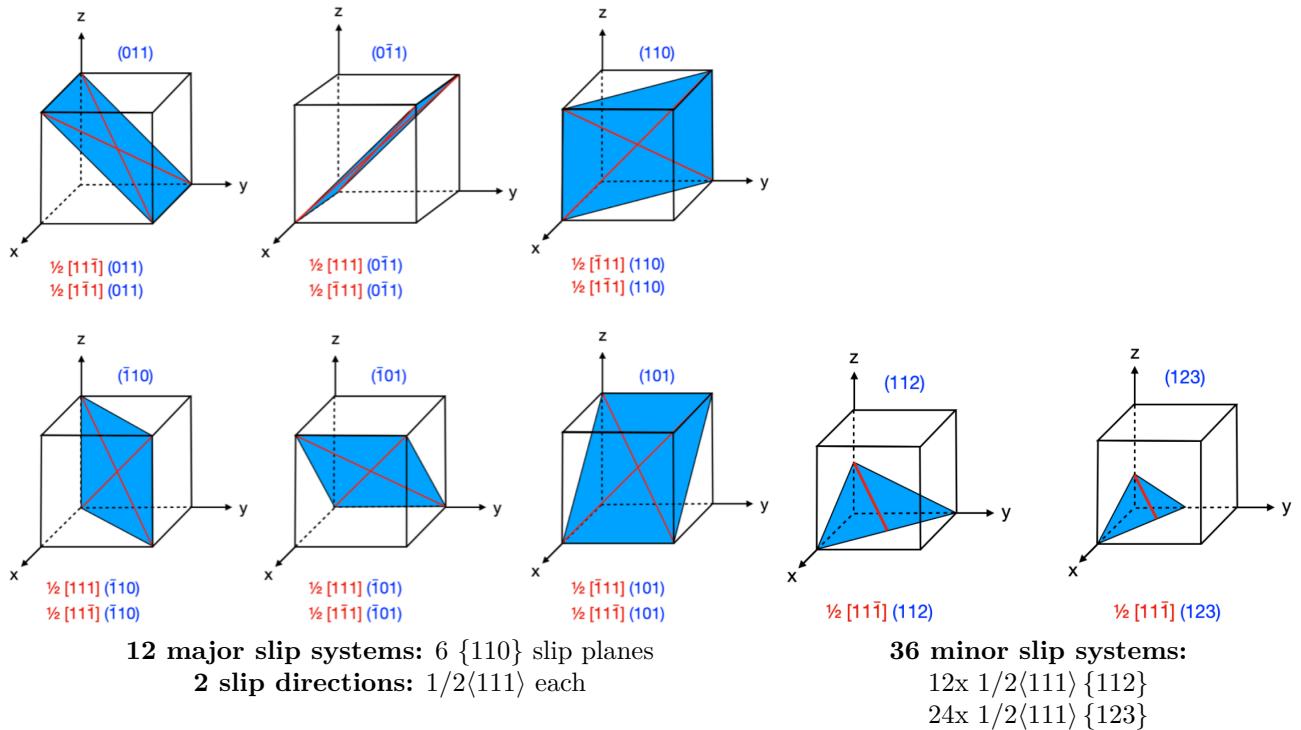
3.5.2 Slip systems in HCP metals (Miller indices)

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)

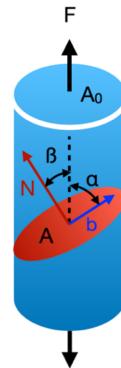
BCC metals have 48 slip systems but are less closely packed, leading to higher strength and lower ductility (e.g. α -Fe, Cr, W, Mo, Ta, Nb)



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



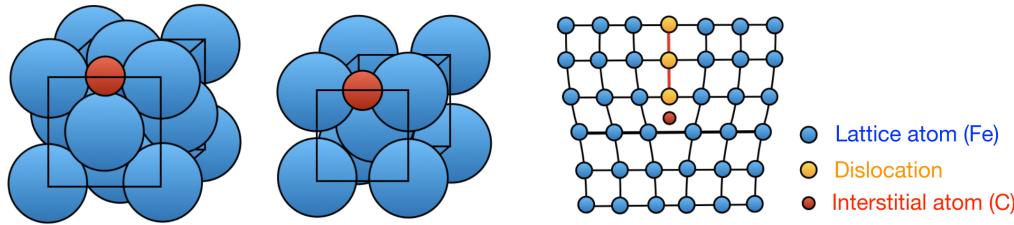
3.7 Correlation between metals crystal structure and ductility

Metal	Ductility	Packing structure	Slip systems	Slip system orientation
FCC	Highest ductility among metals	Closest-packed (74%)	4 slip planes \rightarrow 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 \rightarrow 3 slip systems	Low probability of favorable orientation (-45° to load axis)

3.8 Particularities in BCC metals

3.8.1 Cottrell atmospheres and Dislocation pinning

- In α -iron with a BCC structure (ferrite), the octahedral sites for interstitial atoms such as carbon or nitrogen are much smaller than in γ -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

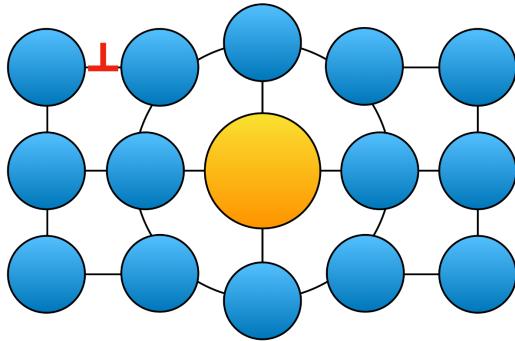
4.0.1 Metals mechanisms

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 precipitates 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 atmospheres 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 jewelry (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 corrosion, UV light or oxidizing agents, food safety, biocompatibility, toxicity

6.1 Failure hypothesis 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 (Fracture 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 :

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

7.1.2 Normal stress

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

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

7.1.3 Shear stress

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

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

7.1.4 Engineering strain ε

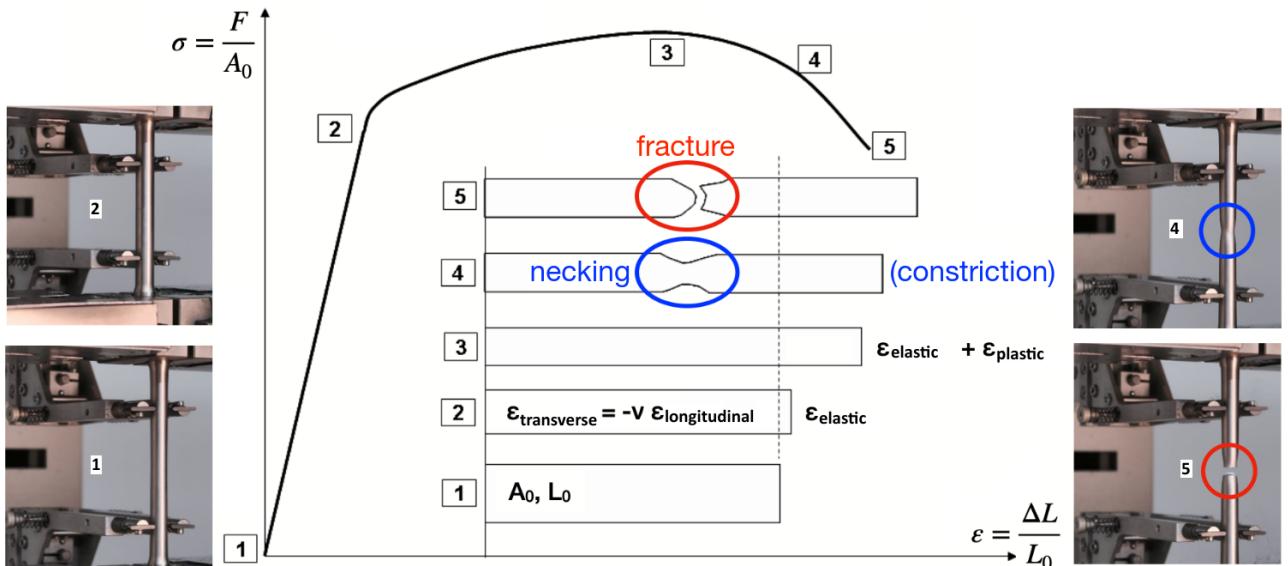
Engineering strain is the ratio of the change in length to the original length of a material under load:

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

7.1.5 Hooke's law

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

$$\sigma = E \cdot \varepsilon$$



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
α -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

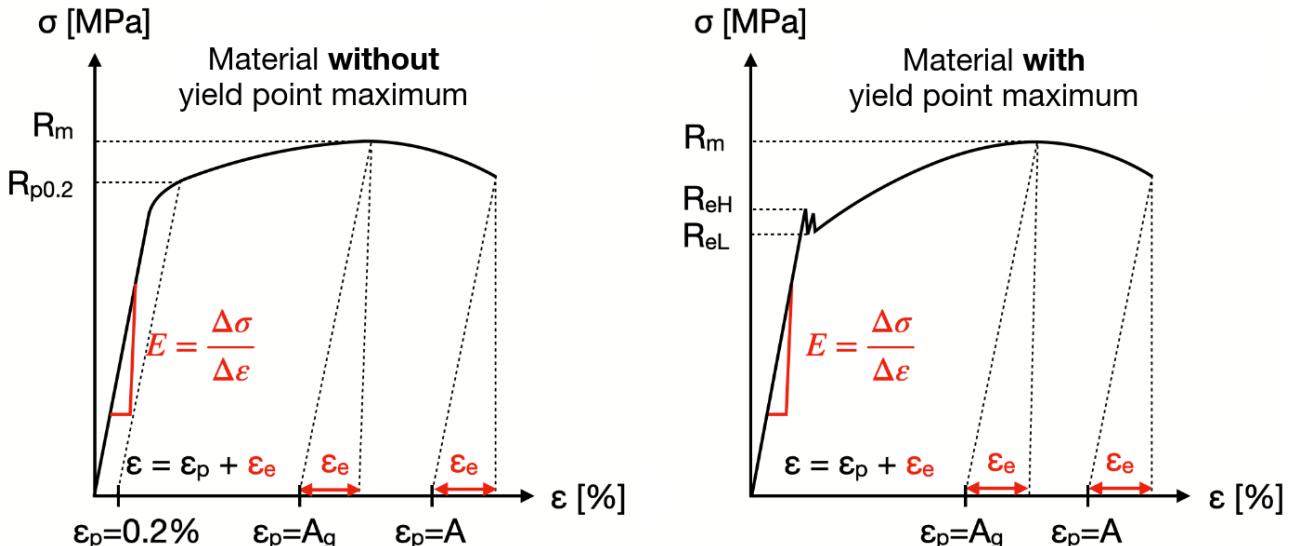
If the applied force is too big:

- 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:

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

7.4.2 Yield stress R

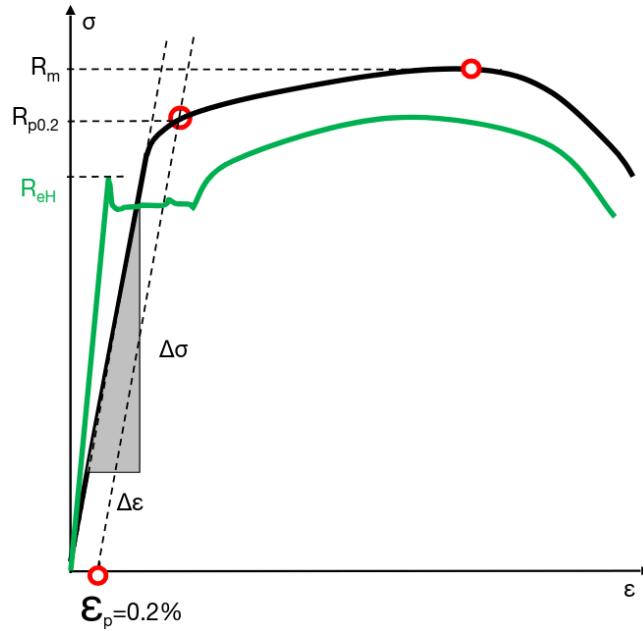
Yield stress R is the stress, expressed in MPa, at which plastic deformation begins:

- 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

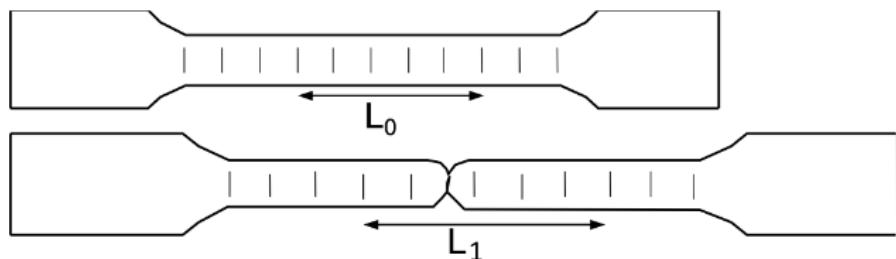


Note: representation not scaled; the elastic region is drawn much too flat

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 $A_{50\text{mm}}$)



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

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:

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

7.6 True Stress and True Strain

7.6.1 True stress σ^*

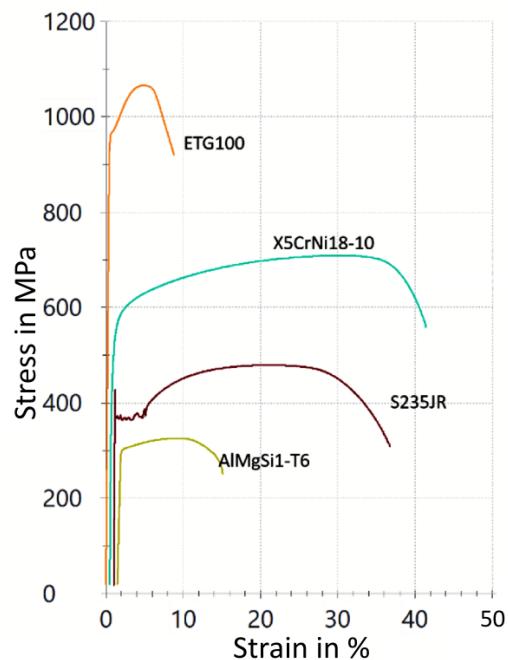
True stress is the force related to the **true** cross-section (which is constantly contracting):

$$\sigma^* = \sigma (1 + \varepsilon)$$

7.6.2 True strain ε^*

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

$$\varepsilon^* = \ln (1 + \epsilon)$$



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 isochronous 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 (determined 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 $R_{p0.2}$ (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 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

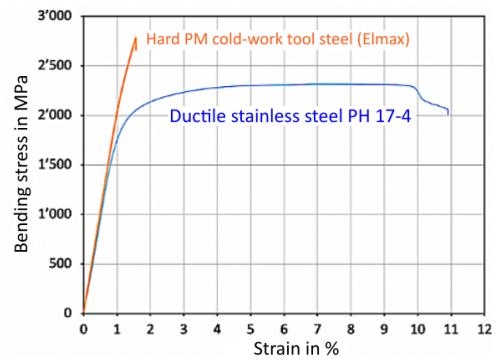
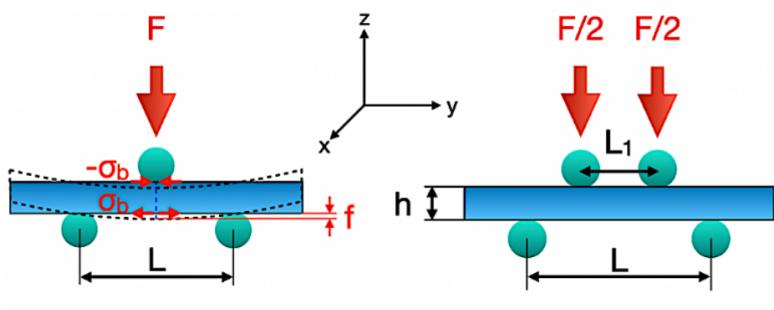
8.1.1 Flexural strength (bend strength) σ_b

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

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

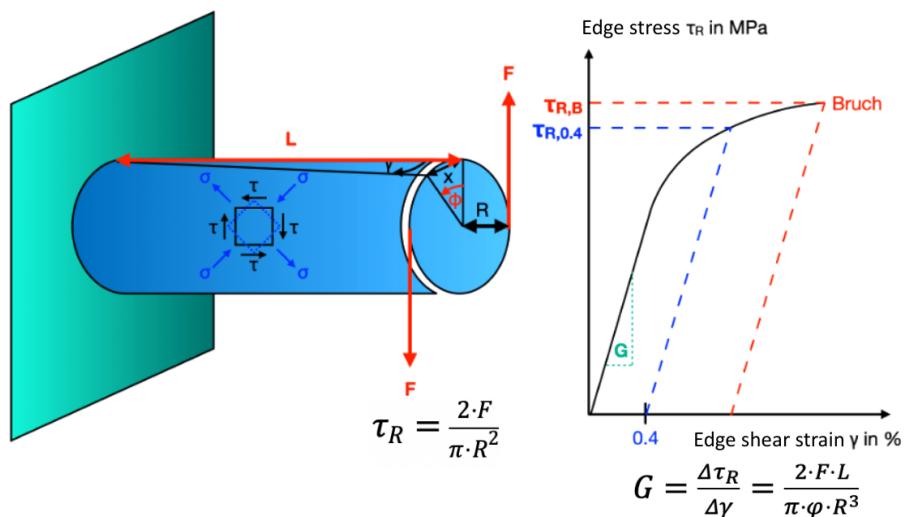
The Young's modulus E is then calculated as:

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



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 $\tau_{R,0.4} > R_{p0.2}$ from tensile tests
- $\boxed{\tau_{R,0.4} \approx 0.58 \cdot R_{p0.2}}$

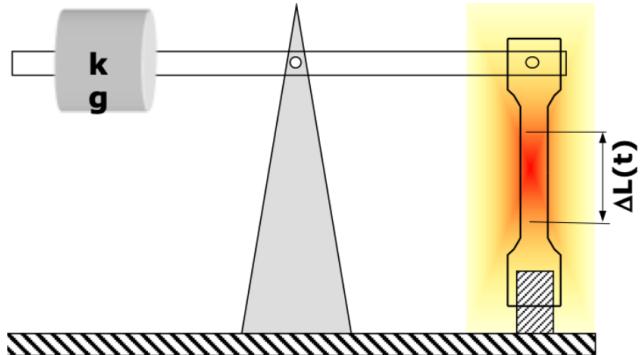


8.3 Creep and Relaxation Tests (High temperatures)

- 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.

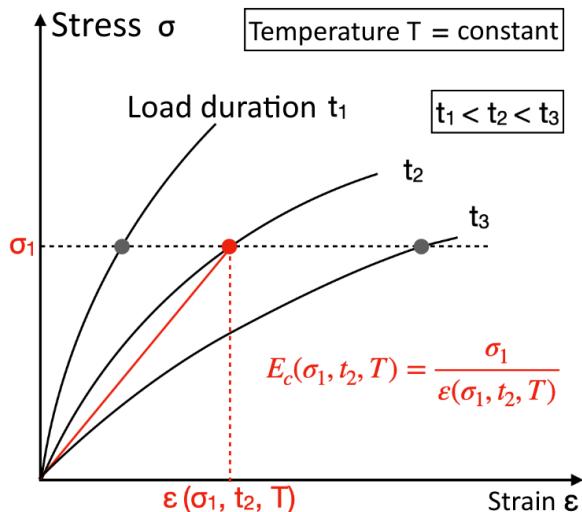
8.3.1 Creep test

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 Isochronous $\sigma - \varepsilon$ -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 isochronous $\sigma - \varepsilon$ -diagram
- For different temperatures, a separate diagram is created for each temperature



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

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

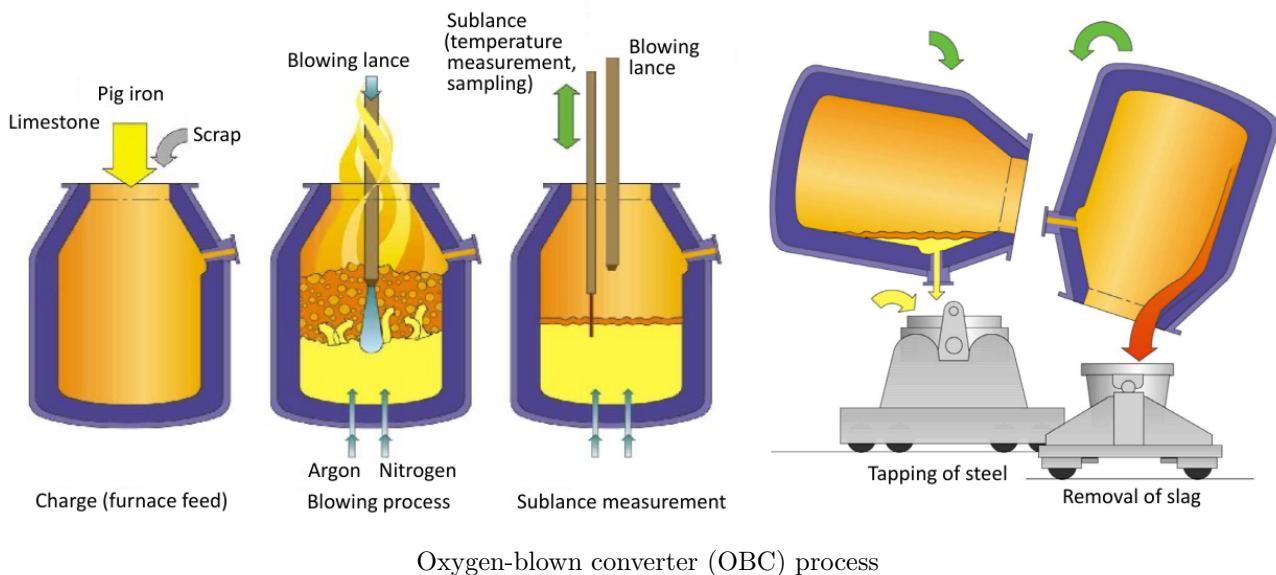
- Process: reduction of iron oxide with coke $\text{Fe}_2\text{O}_3 + 3\text{C} \rightarrow 2\text{Fe} + 3\text{CO}$
- Product: pig iron (3-5% C, also contains Mn, Si, S, P)
- Furnace dimensions: $\sim 30\text{m}$ tall, $\varnothing 10\text{-}14\text{ m}$
- Typical input/output per day:
 - 16'000 t ore, 4'500 t coke, 14'000 t air
 - \rightarrow 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)



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)

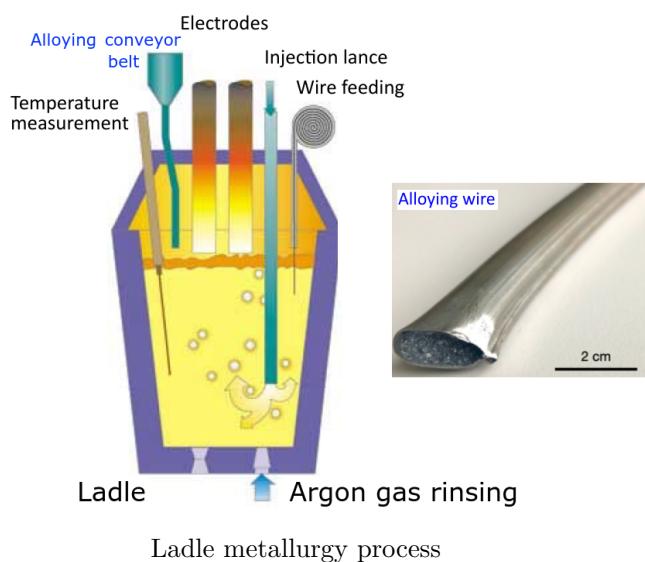
9.3.1 Purifying and alloying of the crude steel

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 achieving maximum purity:

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



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 intercrysalline 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

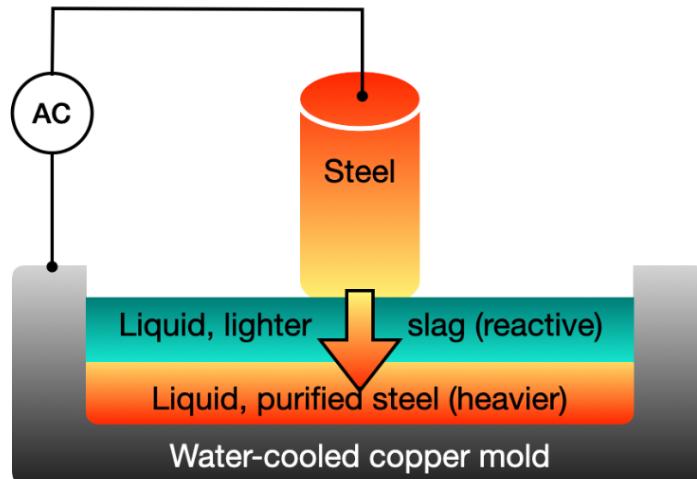
- Melt droplets pass through slag and solidify in a **water-cooled copper mold**
- Rapid solidification procedures:
 - Fine-grained structure
 - Homogeneously distributed carbides

Applications

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

Alternative method

- Powder metallurgy (PM) can achieve 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 CO₂ emissions, but high costs
- Hydrogen supply:
 - H₂ produced by electrolysis of water
 - Powered with renewable electricity (wind, solar)
- Iron ore reduction
 - Iron ore directly reduced with **green hydrogen** (DRI) to form sponge iron
 - By-product: **water vapor** instead of CO₂
- 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

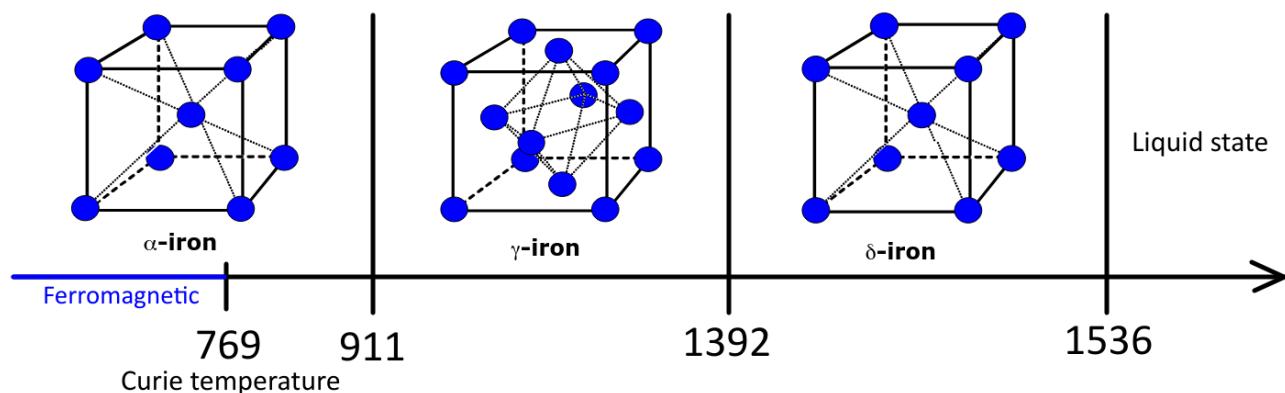
δ -iron is a phase of iron with a BCC structure. It is stable above 1392°C, and it's not ferromagnetic. Has a limited technical relevance.

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 distortion 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 Phase transformations

10.2.1 Microstructure formation of Steel (Slow Cooling)

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](#))

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.

Brittle Material that fractures without significant 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.

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.

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.

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.

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.

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 subjected 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.

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.

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.

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.

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

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

B Nomenclature

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 → 210 GPa for steel
G	Shear modulus

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
$R_{p0.2}$	0.2% yield strength
HV	Vickers hardness

Transformations and Processes abbreviations

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
HSS	High-Speed Steel
NHD	Nitriding Hardness Depth
OBC	Oxygen-Blown Converter
OHF	Open Hearth Furnace
PM	Powder Metallurgy

Q+T	Quenching and Tempering
QT	Quenching and Tempering
SHD	Surface Hardening Depth
VAR	Vacuum Arc Remelting
ZTU/CCT	Continuous Cooling Transformation diagram