

# 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

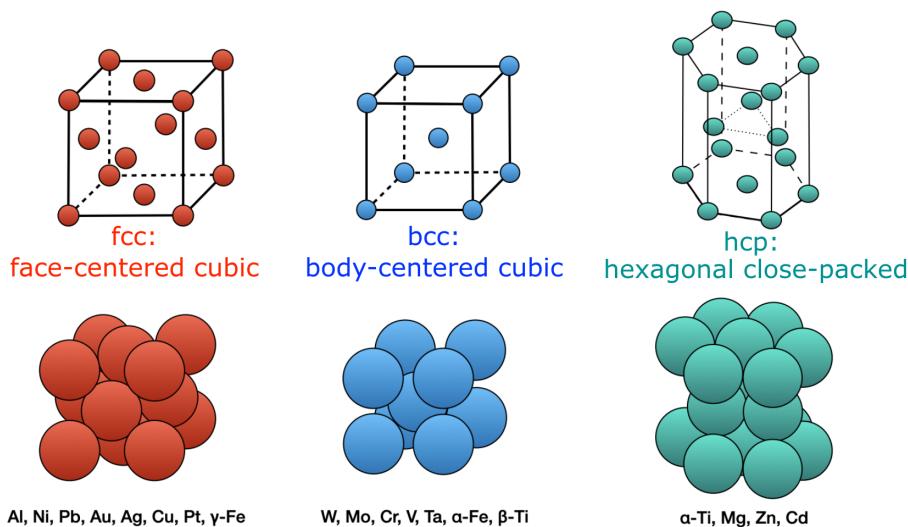
#### 1.1 Material classes and typical properties

Class	4 Typical Properties
<b>Metals / Alloys</b>	1) Conductivity (electric, thermal) 2) Ductility / malleability 3) Castable 4) Shiny (reflective)
<b>Ceramics</b>	1) High temperature resistance 2) Compression resistance 3) Insulator (electric, thermal) 4) Wear resistance
<b>Polymers</b>	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:  

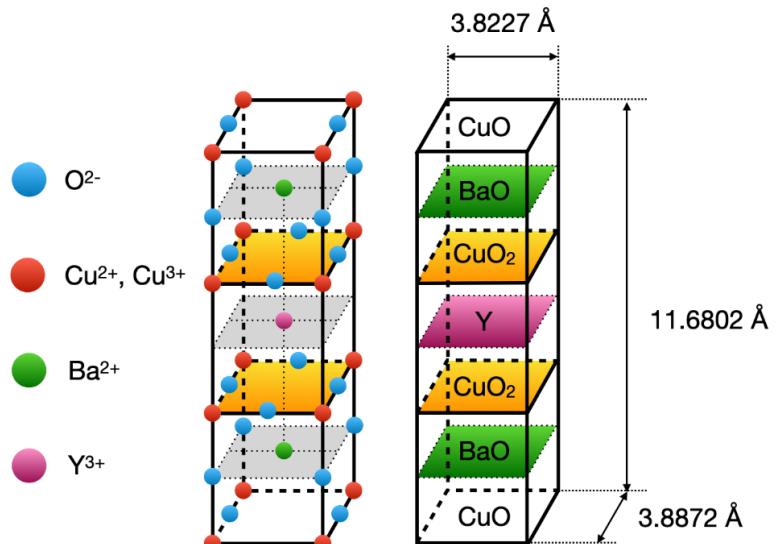
$$\phi = \frac{\sqrt{3}\pi}{8} \approx 68\%$$
- Has many slip systems (6)
- Not closest packed direction
- Very few slip systems (3)
- Closest packed direction

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

### 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)

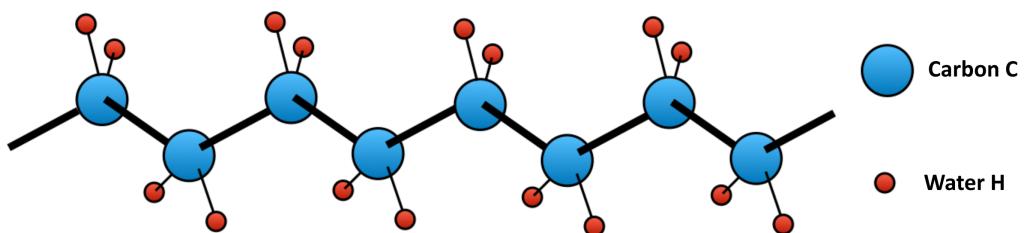


YBCO superconducting ceramic with layered perovskite-like structure

### 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

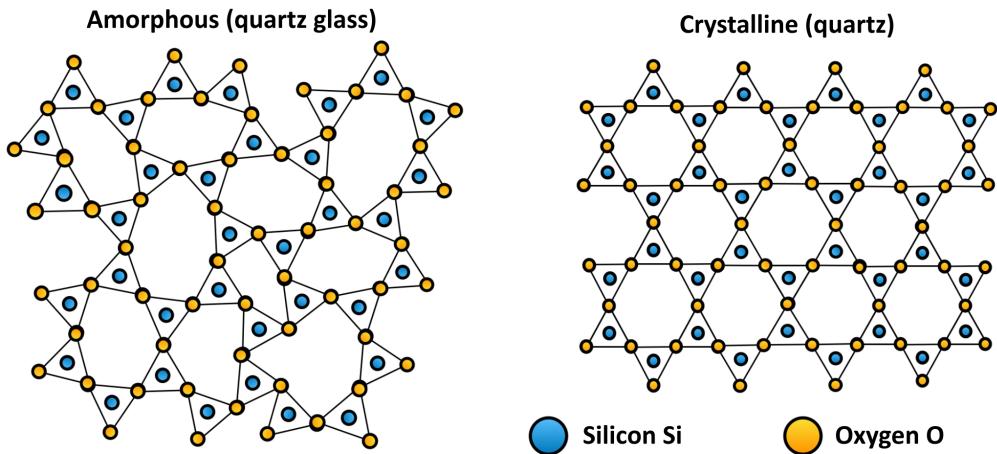
### 1.5 Amorphous and crystalline materials

#### 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

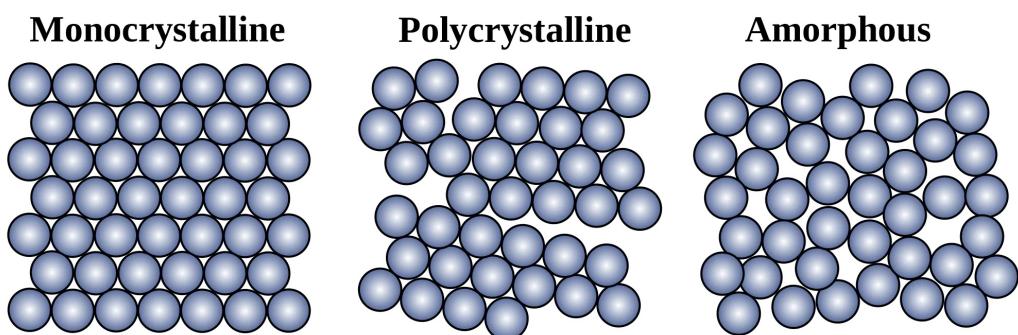
**Only for special applications, expensive**

- 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

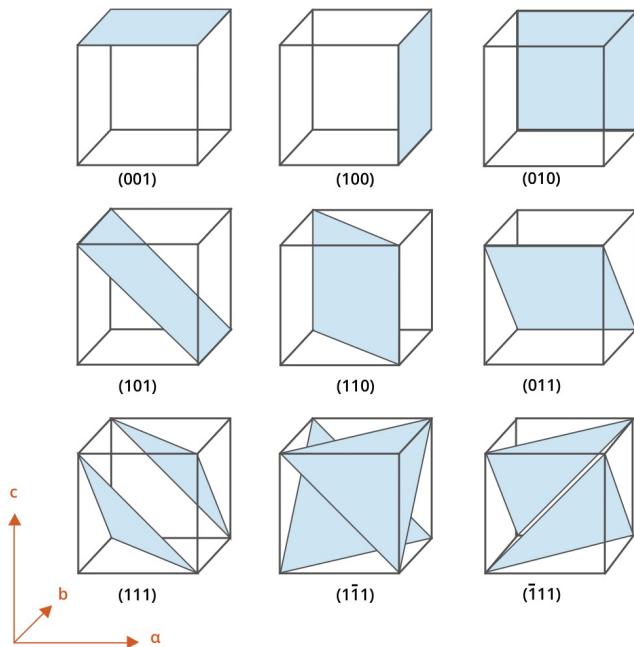
- Anisotropic: Properties depend on direction (e.g. single crystals, wood, composites)
- Isotropic: Properties do not depend on direction (e.g. polycrystalline metals, amorphous materials)

### 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

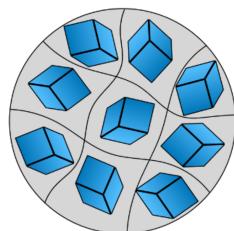
In short, the Miller indices are the reciprocals of the fractional intercepts that the plane makes with the crystallographic axes:



## 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.

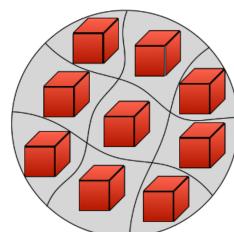


Polycrystalline material without texture

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

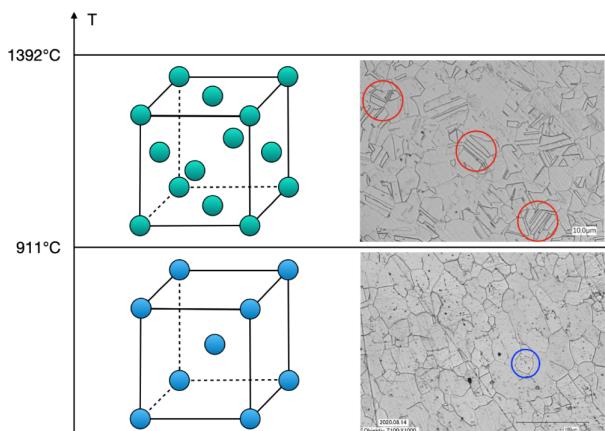
- Isotropic (e.g. glass or amorphous metals)

## 1.9 Polymorphism (Allotropy)

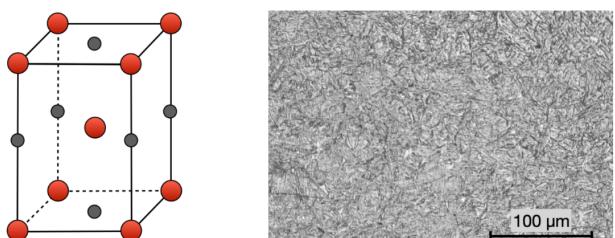
Some materials may exhibit more than one crystal structure:

- 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)

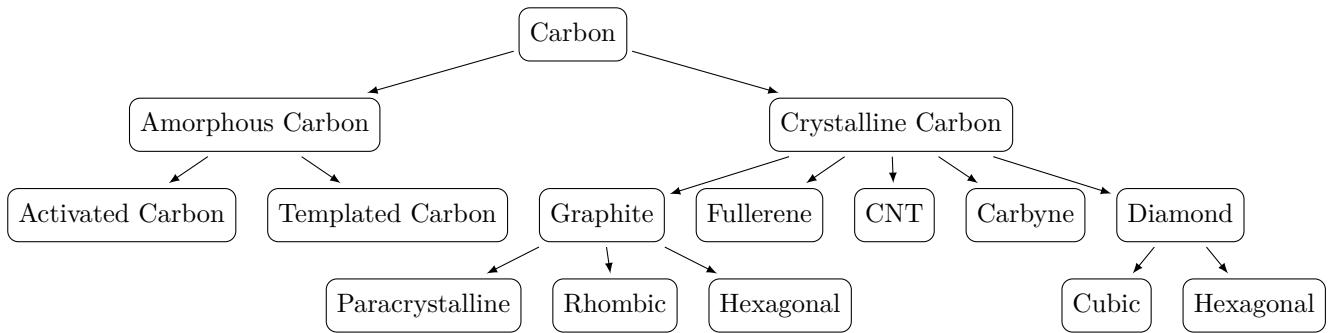


Slow Austenite transformation in steel: Ferrite



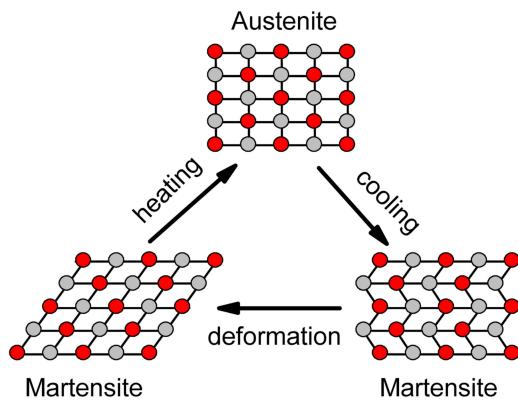
Fast Austenite transformation: Martensite

### 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:

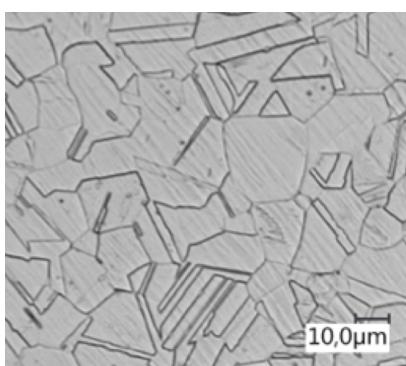
- A phase can be crystalline or amorphous
- At the phase boundaries, a sudden change in structure, properties and chemical composition occurs

Polycrystalline materials can consist of:

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

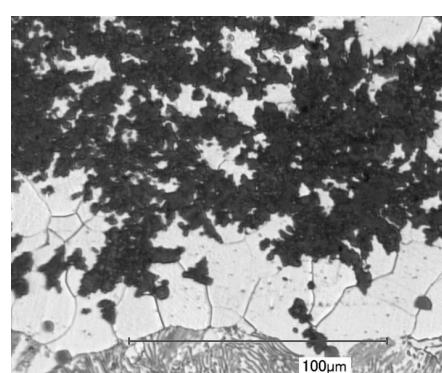
### 1.10.1 Homogeneous microstructure

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. Ni<sub>3</sub>Ti, Fe<sub>3</sub>C, ...)
  - (Impurity particles, e.g. added ceramic particles or slag residues)

## 2 Most important metal structures and crystal lattice defects

### 2.1 Lattice defects

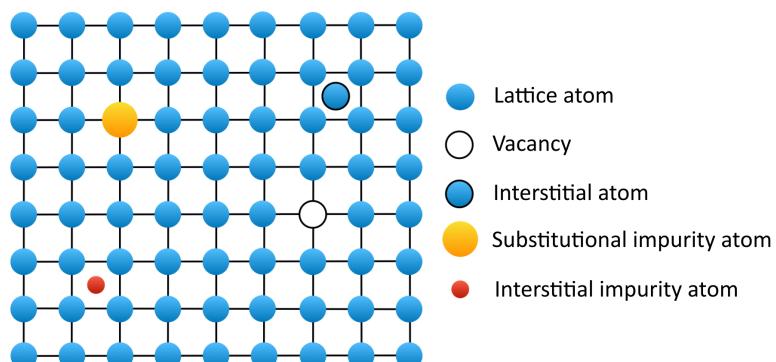
Lattice defects are irregularities in the crystal structure:

- **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.

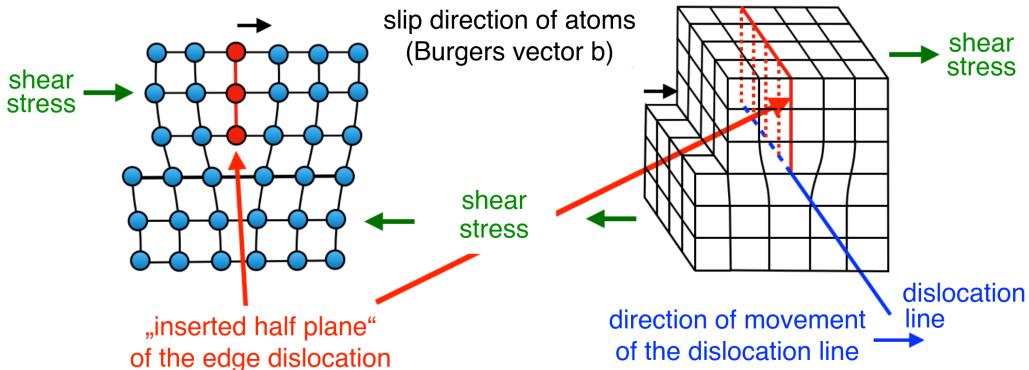


Point defects: vacancy, interstitial atom, substitutional atom

### 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.



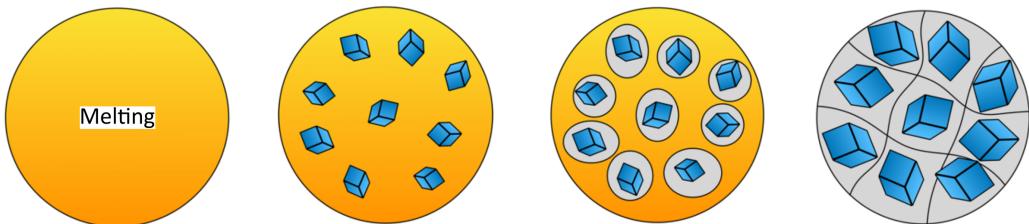
Line defects: edge dislocation, screw dislocation

### 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  $\mu\text{m}$ .



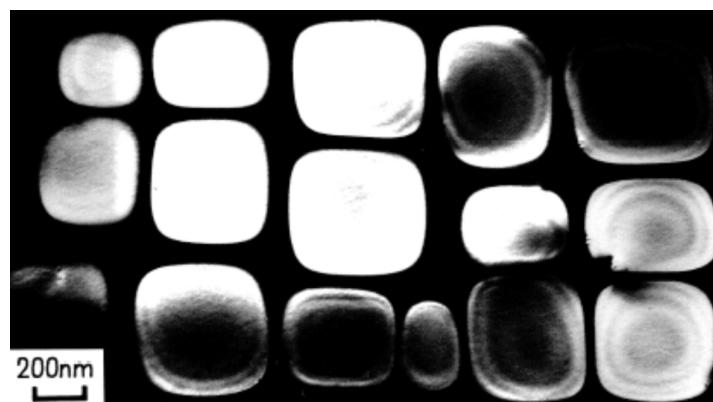
Crystallization from a melt:

(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  $\text{Ni}_3\text{Al}$  precipitates (white) in a Ni solid solution crystal (black)

### 3 Elastic and plastic deformation

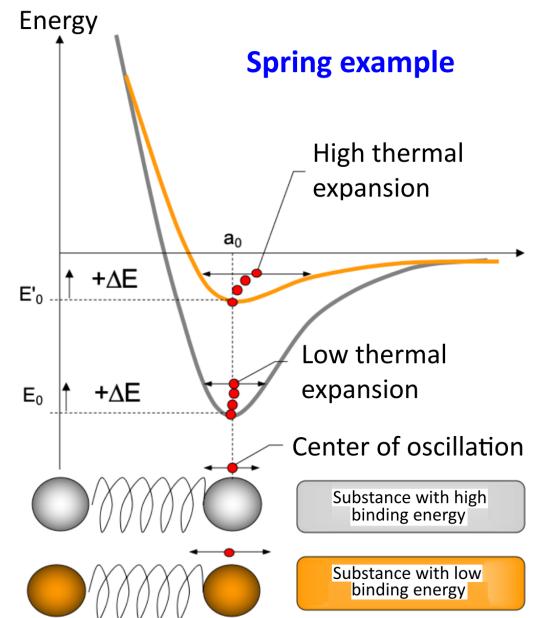
#### 3.1 Elastic deformation

##### 3.1.1 Atomic energy-distance model

The atomic energy-distance model describes the interaction between two atoms.

The coefficient of thermal expansion  $\alpha$  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 $\nu$

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.

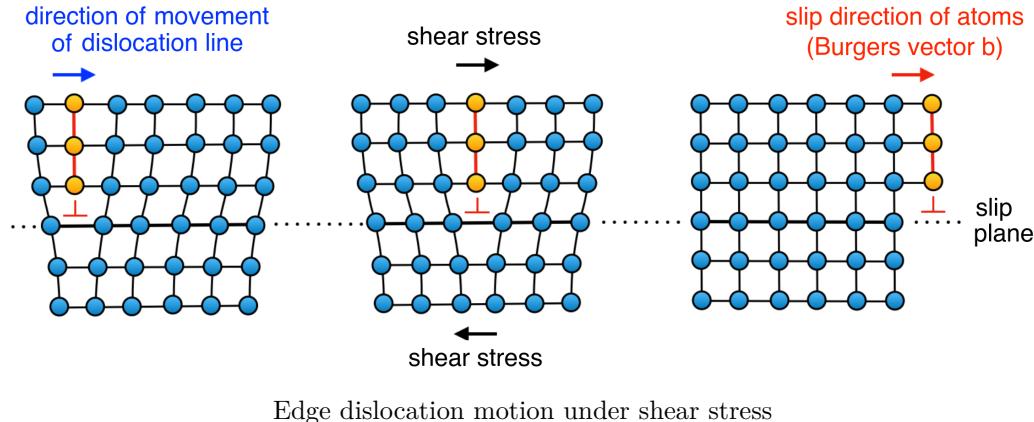
### 3.4 Dislocation Slip Model

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:

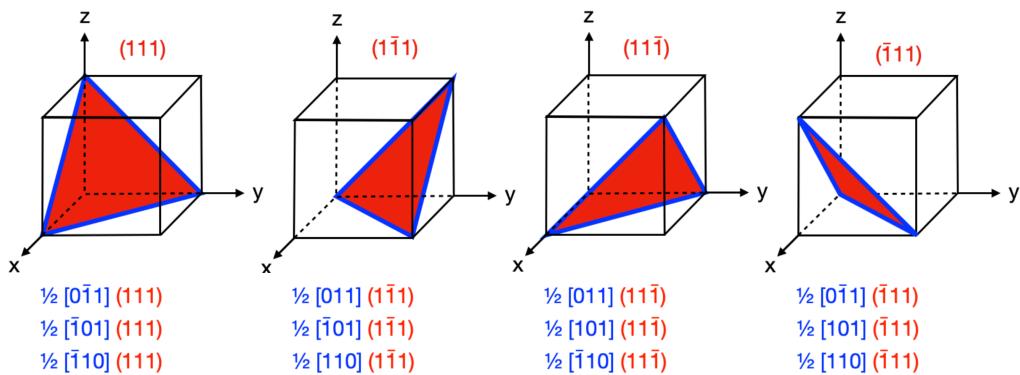
- Inserted half-plane, the end of which forms the dislocation line
- Dislocation moves on densely packed slip planes



### 3.5 Slip systems

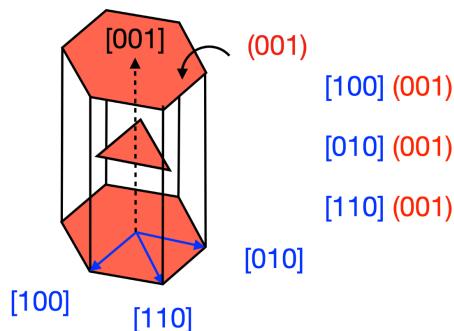
#### 3.5.1 Slip systems in FCC metals (Miller indices)

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



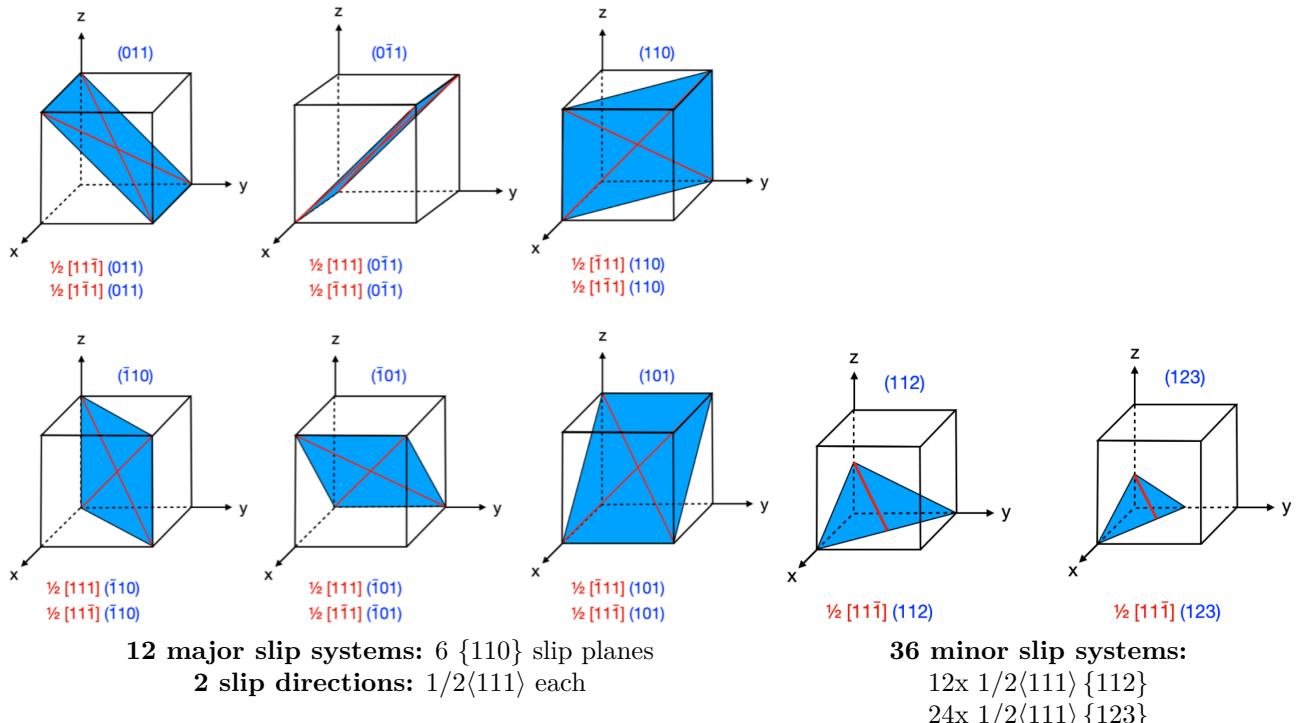
#### 3.5.2 Slip systems in HCP metals (Miller indices)

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)

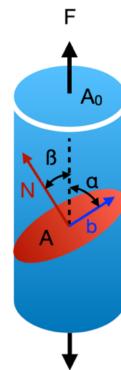
BCC metals have 48 slip systems but are less closely packed, leading to higher strength and lower ductility (e.g.  $\alpha$ -Fe, Cr, W, Mo, Ta, Nb)



### 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  $45^\circ$  to the load axis



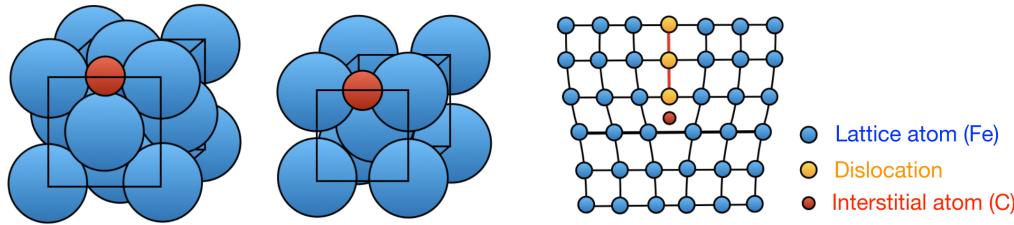
### 3.7 Correlation between metals crystal structure and ductility

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 ( $-45^\circ$ to load axis)

### 3.8 Particularities 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

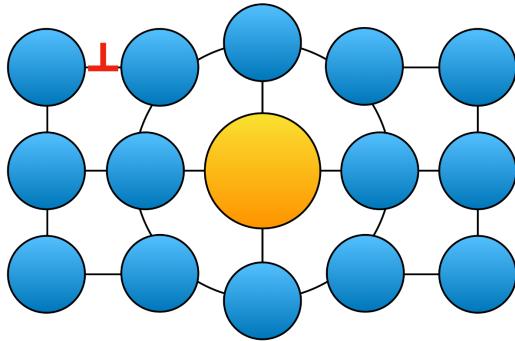
#### 4.0.1 Metals mechanisms

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	<b>Substitution / Interstitial atoms</b> with concentration of $c$ in the solid solution crystal	Solid solution hardening	$\Delta R_{p0.2} \sim c^{1/2}$
1-D	<b>Dislocations</b> (dislocation density $N$ )	Strain (cold-work) hardening	$\Delta R_{p0.2} \sim N^{1/2}$
2-D	<b>Grain boundaries</b> defining an average grain size of $d$	Grain boundary hardening <b>strength and ductility still good</b>	$\Delta R_{p0.2} \sim d^{-1/2}$
3-D	<b>Coherent precipitates</b> 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 $\sigma$

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  $\sigma$ , 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  $S_0$ :

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

### 7.1.4 Engineering strain $\varepsilon$

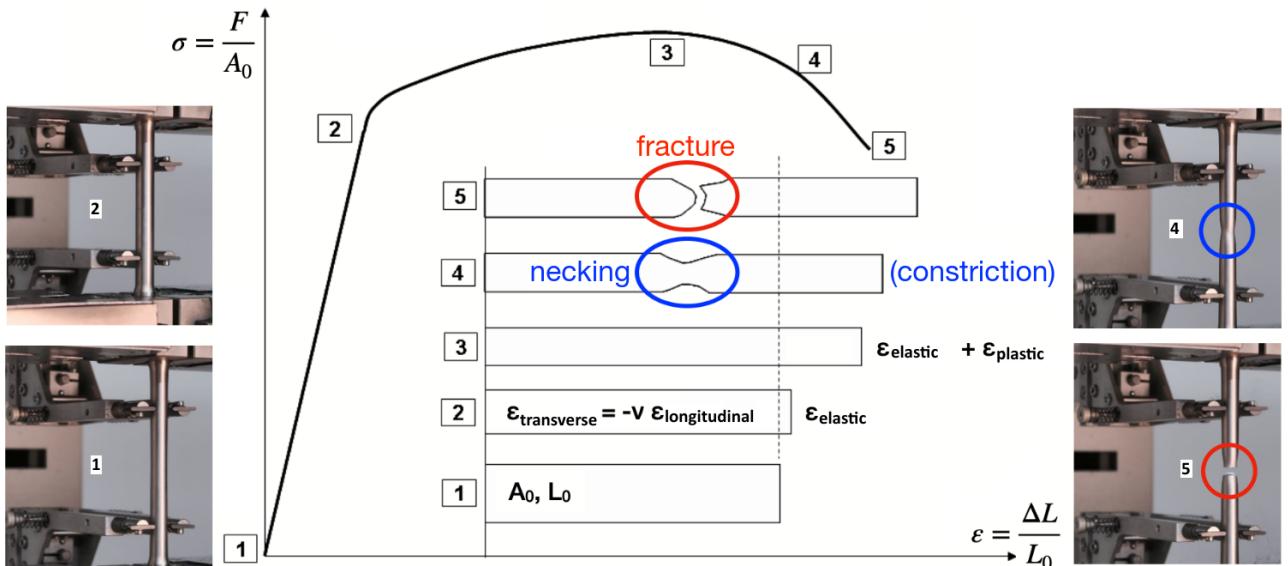
Engineering strain is the ratio of the change in length to the original length of a material under load:

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

### 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 $\nu$	Young's modulus $E$ [N/mm <sup>2</sup> ]	Shear modulus $G$ [N/mm <sup>2</sup> ]
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

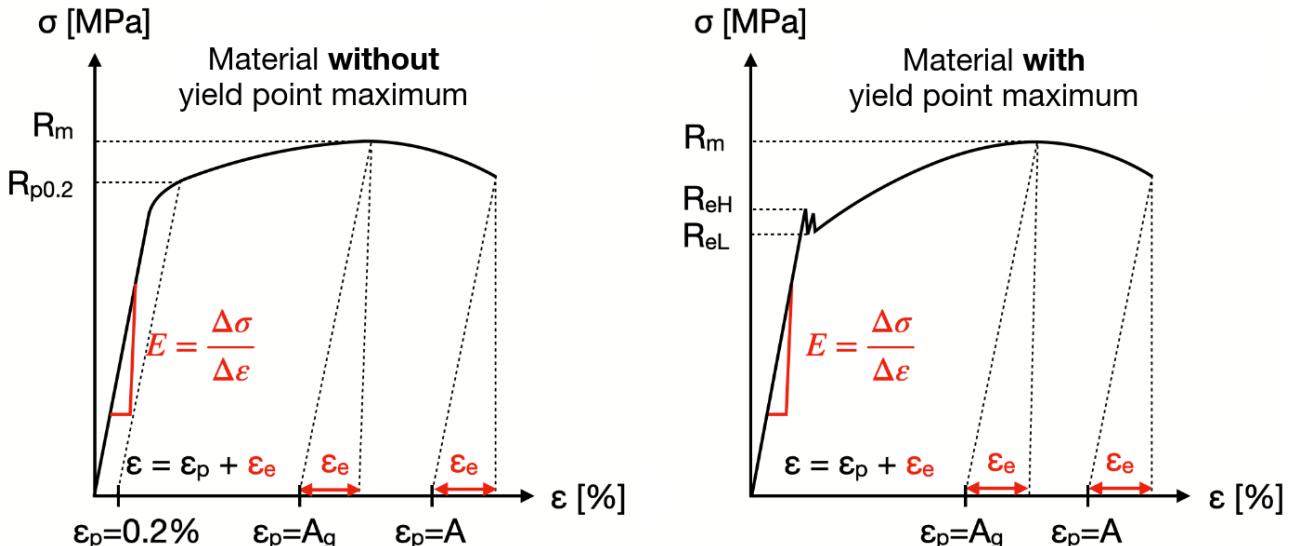
If the applied force is too big:

- 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:

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

### 7.4.2 Yield stress $R$

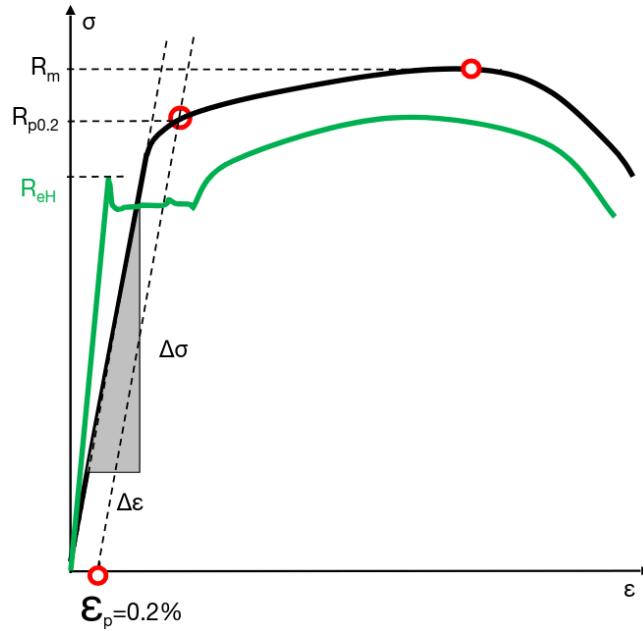
Yield stress  $R$  is the stress, expressed in MPa, at which plastic deformation begins:

- 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

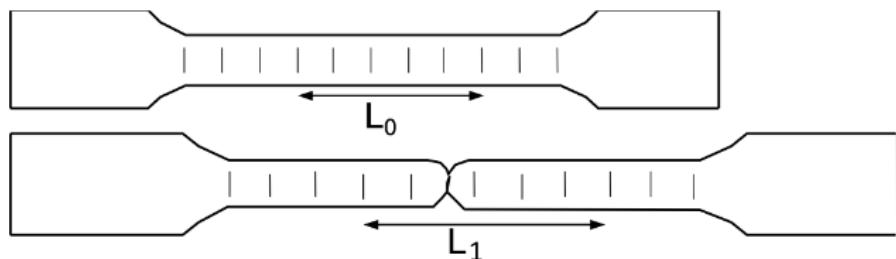


Note: representation not scaled; the elastic region is drawn much too flat

### 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 $\sigma^*$

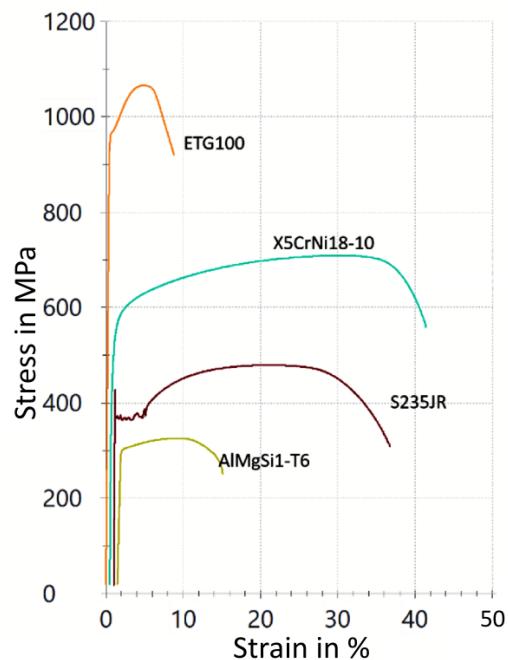
True stress is the force related to the **true** cross-section (which is constantly contracting):

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

### 7.6.2 True strain $\varepsilon^*$

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  $\sigma_y$  and yield strain  $\varepsilon_y$
  - Fracture stress  $\sigma_b$  and fracture strain  $\varepsilon_b$

## 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  $\sigma$  and strain  $\varepsilon$
- 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  $\nu$

## 8 Other quasi-static mechanical tests

### 8.1 Bending test

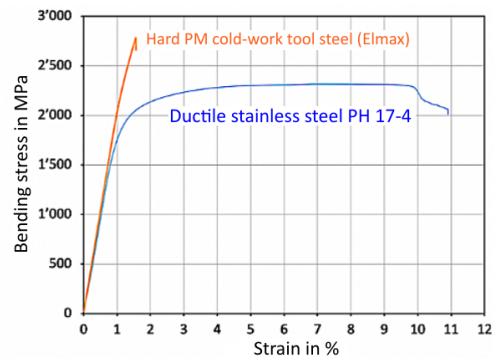
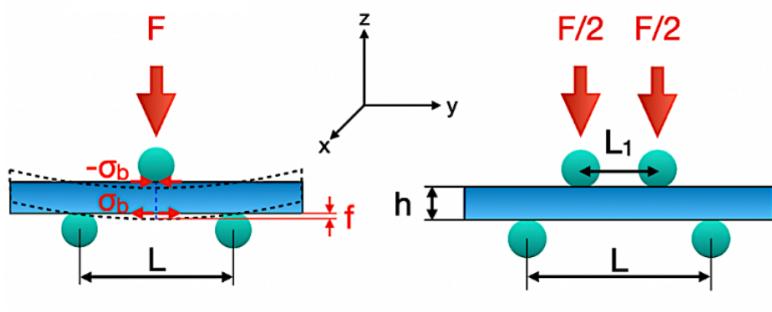
#### 8.1.1 Flexural strength (bend strength) $\sigma_b$

The bend strength is the peripheral edge stress  $\sigma_b$  in the fracture point:

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

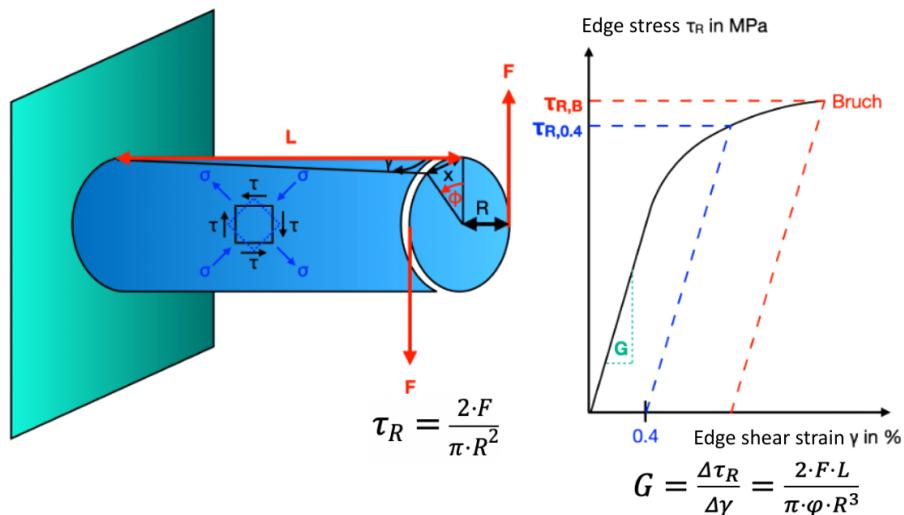
The Young's modulus  $E$  is then calculated as:

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



### 8.2 Torsion test

- Less significant than tensile or bending tests
- Peripheral edge shear stress  $\tau_R$  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
- $\boxed{\tau_{R,0.4} \approx 0.58 \cdot R_{p0.2}}$

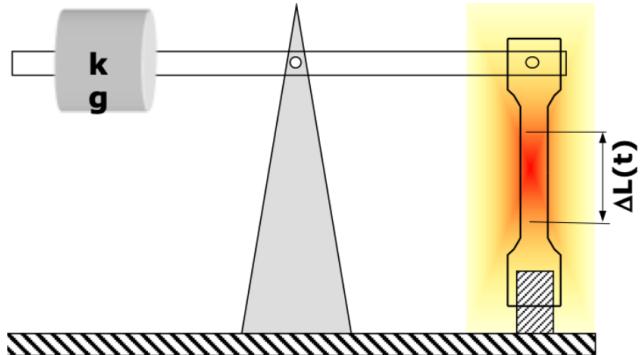


### 8.3 Creep and Relaxation Tests (High temperatures)

- 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.

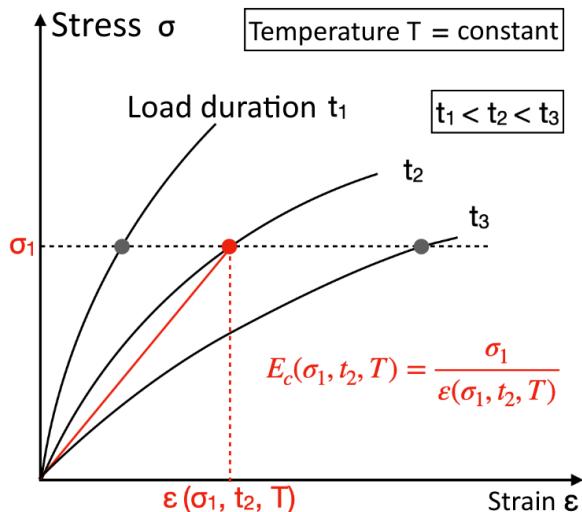
#### 8.3.1 Creep test

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



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

## 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](#))

**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.

**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.

**Isotropy** Direction-independent properties of a material ([Amorphous](#))

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

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

**Poisson's ratio**  $\nu$  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.

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

**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.

**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

$A_g$  Uniform strain

$A$  Fracture strain

$A_n$  Elongation measured with  $L_0 = n\sqrt{S_0}$

### Elastic moduli

$E$  Young's modulus

$G$  Shear modulus

### Ratios

$\nu$  Poisson's ratio

### Strength measures

$R_{p0.2}$  0.2% yield strength

$R_{eH}$  Upper yield point

$R_m$  Tensile strength