Materials Lab
HSLU, Semester 3

Matteo Frongillo

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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

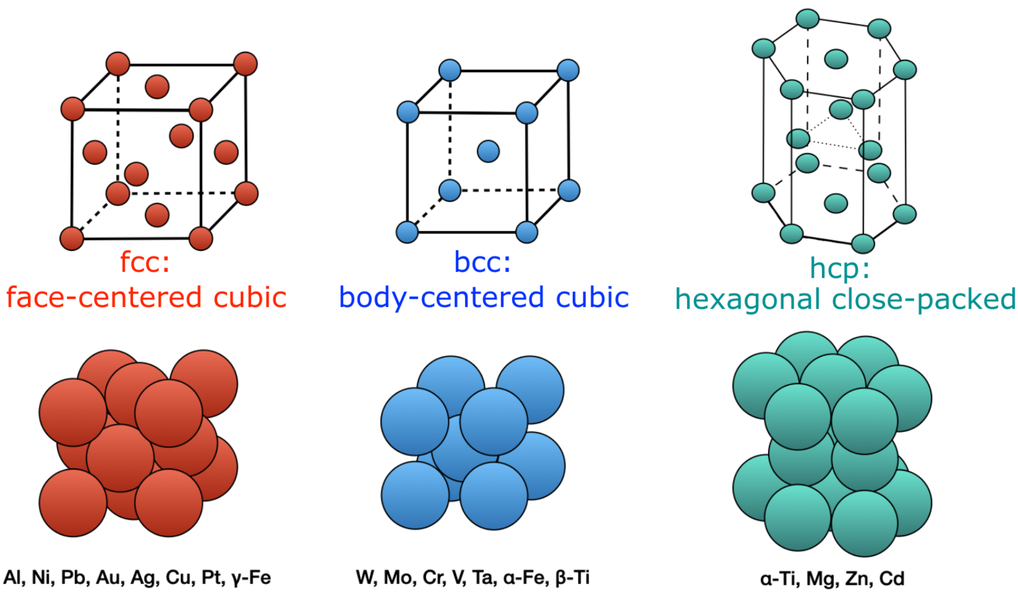
1.1 Material classes and typical properties

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

- Packing efficiency: 74%
- Has many slip systems (12)
- Closest packed direction

BCC (Body-centered cubic)

- Packing efficiency: 68%
- Has many slip systems (6)
- Not closest packed direction
- Cottrell atmosphere

HCP (Hexagonal close-packed)

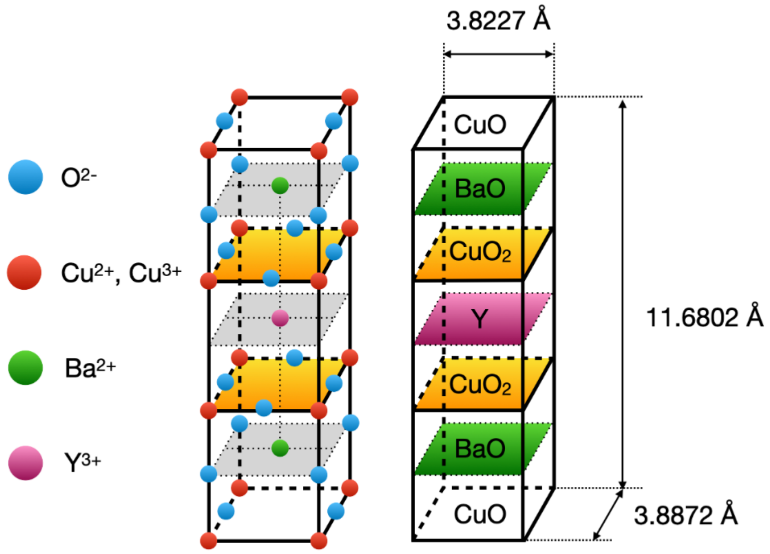
- Packing efficiency: 74%
- Very few slip systems (3)
- Closest packed direction

$$\boxed{\text{Packing efficiency} = \frac{\text{Volume occupied by atoms in unit cell}}{\text{Total volume of unit cell}} \cdot 100\%}$$

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)

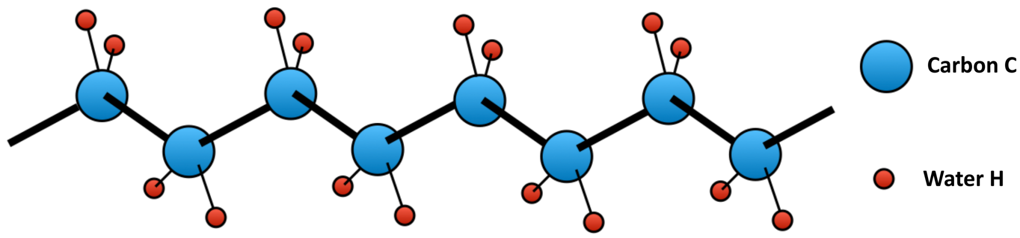


YBCO superconducting ceramic with layered perovskite-like structure

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

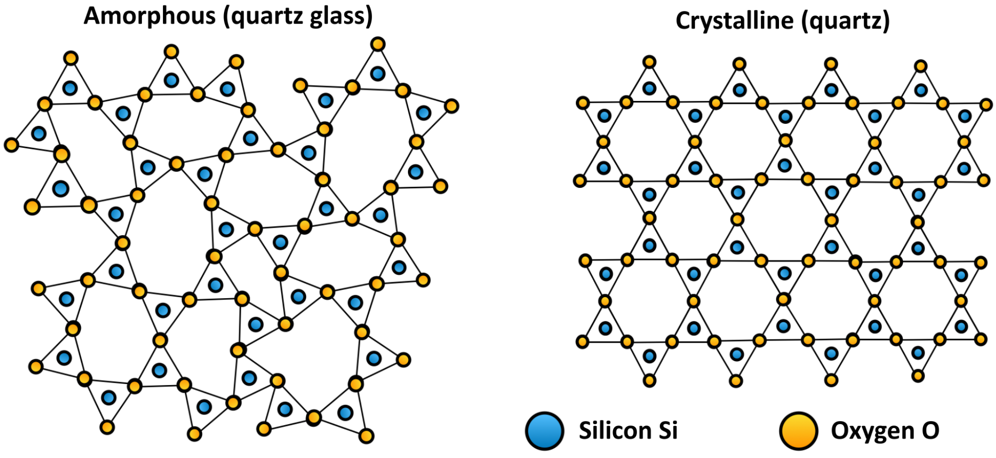
1.5 Amorphous and crystalline materials

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

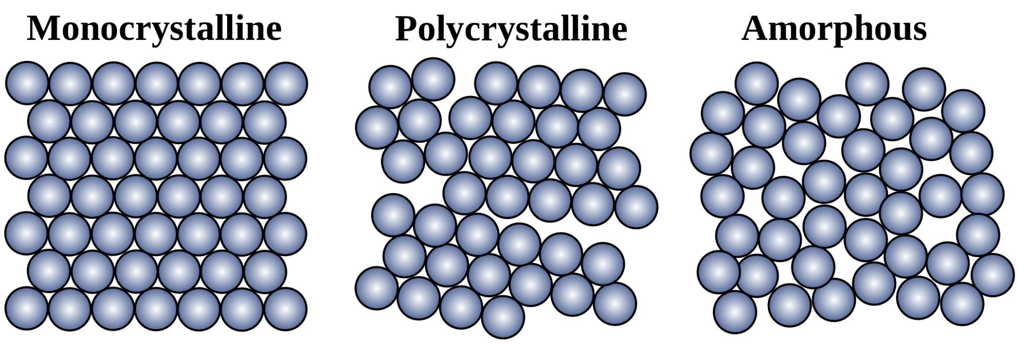
Only for special applications, expensive

- 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

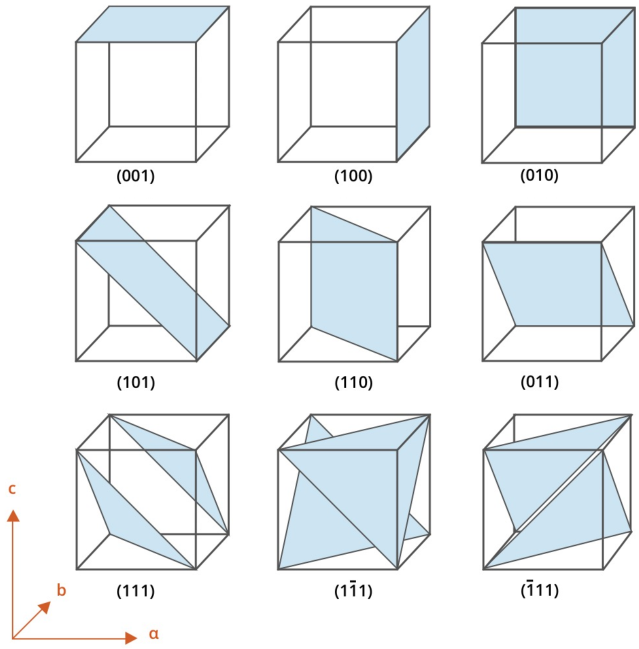
- Anisotropic: Properties depend on direction (e.g. single crystals, wood, composites)
- Isotropic: Properties do not depend on direction (e.g. polycrystalline metals, amorphous materials)

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

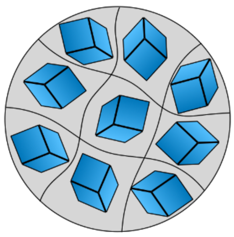
In short, the Miller indices are the reciprocals of the fractional intercepts that the plane makes with the crystallographic axes:



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.

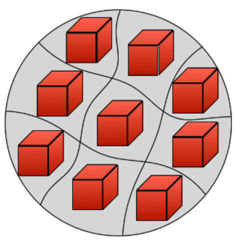


Polycrystalline material without texture

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

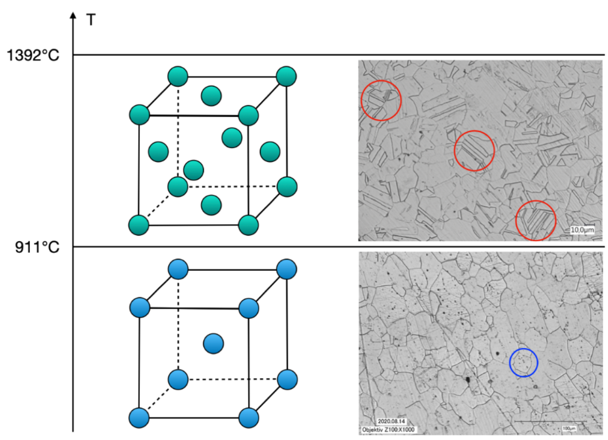
- **Isotropic** (e.g. glass or amorphous metals)

1.9 Polymorphism (Allotropy)

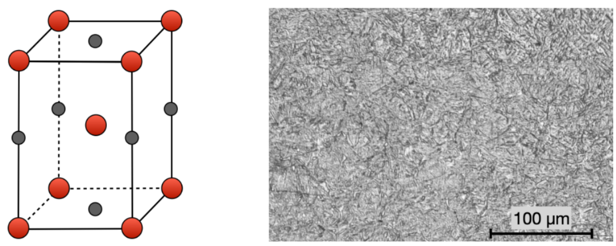
Some materials may exhibit more than one crystal structure:

- 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)

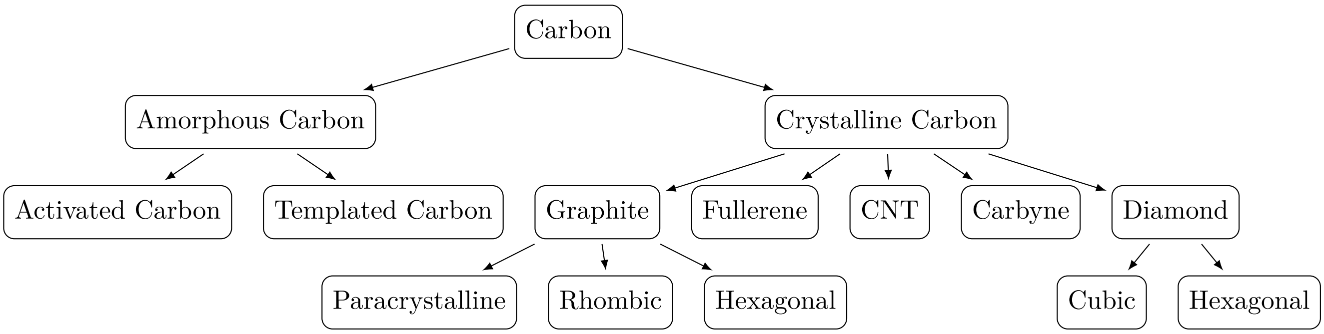


Slow Austenite transformation in steel: Ferrite



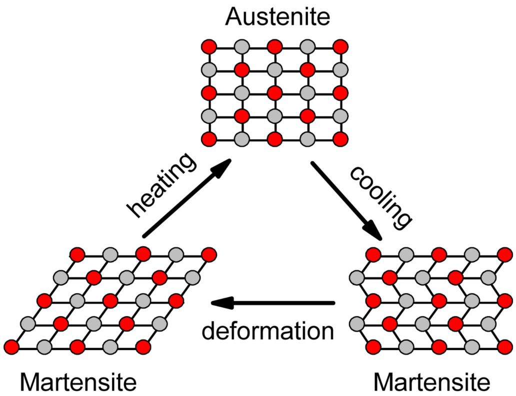
Fast Austenite transformation: Martensite

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:

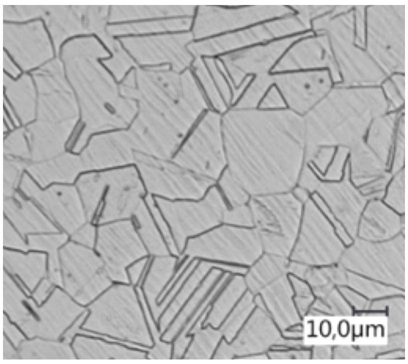
- A phase can be crystalline or amorphous
- At the phase boundaries, a sudden change in structure, properties and chemical composition occurs

Polycristalline materials can consist of:

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

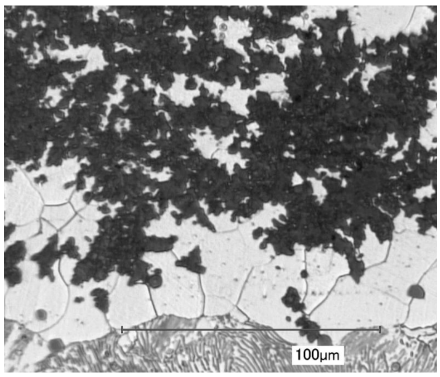
1.10.1 Homogeneous microstructure

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

Appendix

Indices and Abbreviations

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

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

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

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

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

Isotropy Direction-independent properties of a material (Amorphous)

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

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

Homogeneous Uniform composition and properties throughout the material.

Heterogeneous Non-uniform composition and properties throughout the material.

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