Lecture on Materials Science - Microstructure of Materials

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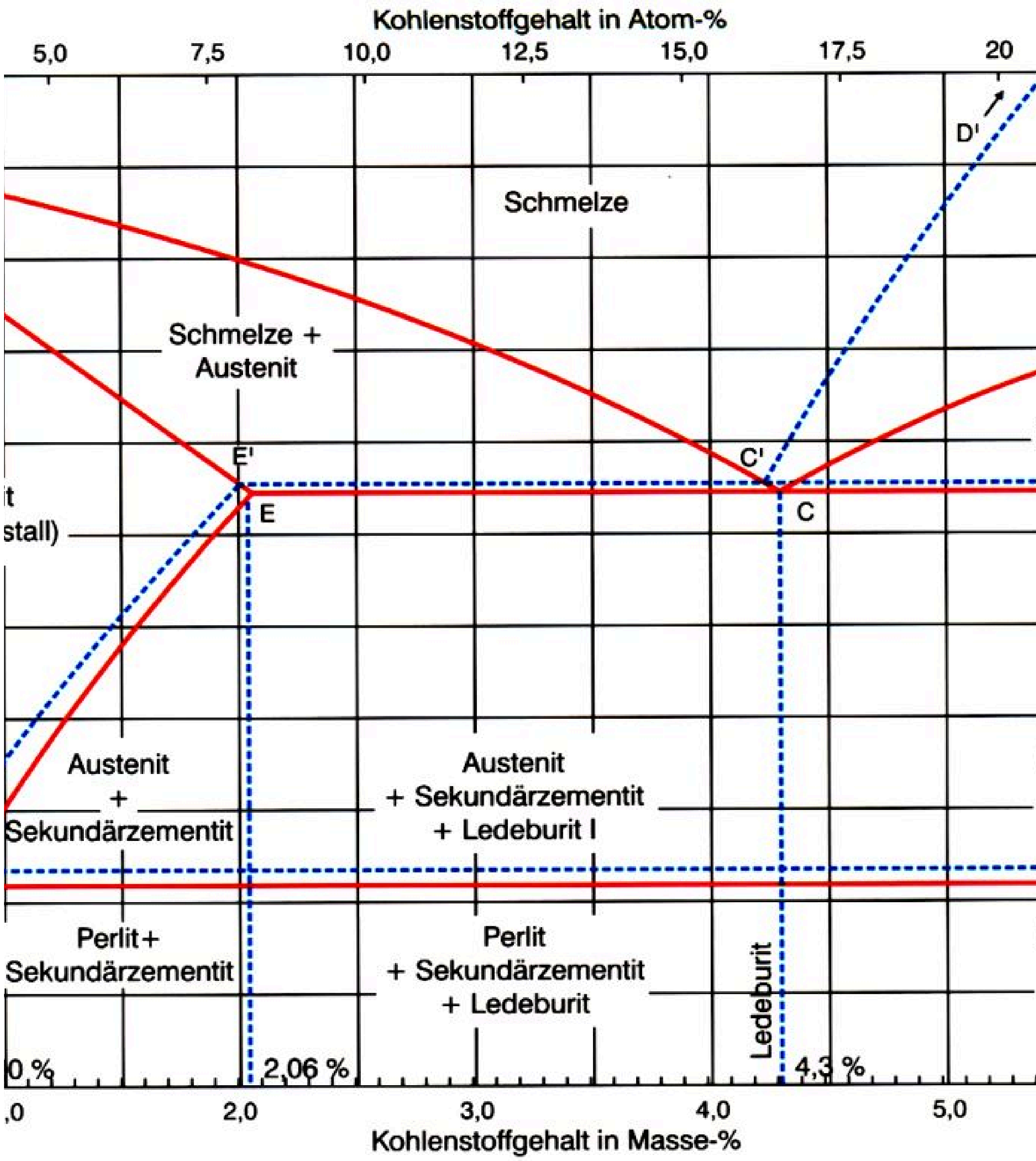
Parts of the script are adopted from Prof. Dr.-Ing. Jürgen Häberle



Content

Terminology

Alloy

- Mixture of multiple types of atoms (*components*) with *metallic character*
- Components:
  - Mostly metallic (Cu, Ni)
  - Non-metallic (C, P, S, N, O)
- Variations:
  - Which components
  - Number of components
  - Concentration of components

Chemical Composition or Concentration

Mass fraction, weight fraction, mass percent (synonym)

$\frac{m_1}{\sum_i m_i} \cdot 100 = m_{1-rel}$ in [%]

E.g., $m_{Cu-rel} = \frac{m_{Cu}}{m_{Cu}+m_{Fe}} \cdot 100$

Masses m of components differ.

Atomic fraction

$\frac{n_1}{\sum_i n_i} \cdot 100 = n_{1-rel}$ in [%]

E.g., $n_{Cu-rel} = \frac{n_{Cu}}{n_{Cu}+n_{Fe}} \cdot 100$

If masses m of components are similar, then n_{rel} and m_{rel} are equal.

Exercise

1 kg alloy 25% Ni - 75% Cu.

What are the masses of Cu and Ni for mass fraction and atomic fraction?

Solution

Mass Fraction

$m_{Ni} = 0.75 \cdot 1kg = 0.75kg$
$m_{Cu} = 0.25 \cdot 1kg = 0.25kg$

Atomic Fraction

$A_{Cu} = 63.54u$ - Atomic mass unit $u = 1.66 \cdot 10^{-27}kg$
$A_{Ni} = 58.69u$
$m = n_{Cu}A_{Cu} + n_{Ni}A_{Ni}$
$n_{Cu} = 0.25n$, $n_{Ni} = 0.75n$
$m = (0.25A_{Cu} + 0.75A_{Ni})n$
$n = \frac{m}{0.25A_{Cu}+0.75A_{Ni}} = 1.00565E + 25$
$m_{Cu} = n_{Cu}A_{Cu} = 0.2449kg$
$m_{Ni} = n_{Ni}A_{Ni} = 0.7551kg$

Phase

Commonly understood in terms of the state of matter (solid, liquid, gas, plasma)

General Definition

A phase is a chemically and physically uniform, homogeneous part of an alloy or matter in general.

Phase changes can be categorized into:

- Transformations
- Precipitations

Transformations

- Unstable lattice modifications convert into stable ones.
- Below an equilibrium temperature (e.g., $\gamma - Fe$ to $\alpha - Fe$).
- In alloys, the configuration of solid solutions can change, altering concentration (e.g., γ-MK to α-MK).

Precipitations

- Solubility decreases (with temperature change)
- Phases (one or more) precipitate out of the solid solution
- Requires mass transport (diffusion) → physical work (heat) and time

Diffusion

- Diffusion, in general, is temperature- and time-dependent
- Involves mass transport

  Described by Fick's First Law:

  $dm_A = -D\frac{dc_A}{dx}Sdt$

  with

  $D = D_0 exp(-\frac{Q_A}{RT})$
- D_0 - Diffusion constant
- Q_A - Activation energy / heat

The model can also be applied to describe gas diffusion from tanks.

Gibbs' Phase Rule

$$F = n - P + 2$$

(for gases and liquids)

F = Number of degrees of freedom; n = Number of components; P = Number of phases

At constant pressure (solid substances):

$$F = n - P + 1$$

For cooling and heating curves in metallic systems, this results in:

F = 0 → A plateau

F = 1 → A gradient change

- Single Phase
- Two Phases
- Solid Solution

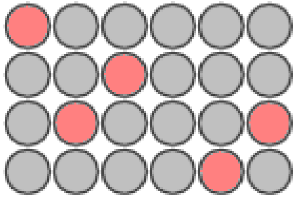
Solid Solutions

- At least 2 types of atoms
- Heterogeneity becomes visible only at atomic dimensions
- Most metals can incorporate a certain number of foreign atoms in their lattice
- This leads to "strain" in the lattice
- Known as "solid solution"

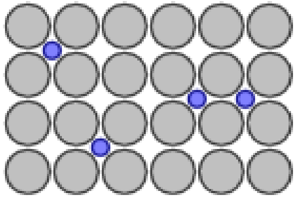
Types of Solid Solutions

Substitutional Solid Solution

- Similar chemical properties
- Similar diameters
- Same crystal lattice



Substitutionsmischkristalle



Einlagerungsmischkristalle

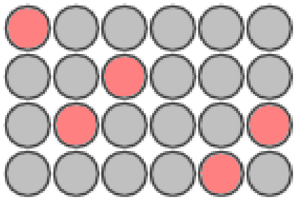
Image Source

Types of Solid Solutions (continued)

Interstitial Solid Solution

- Smaller atoms
- Fit into gaps in the crystal lattice (interstitial atoms)
- Second component is dissolved
- Diameter ratio $f = \frac{d}{D} \leq 0.41$

Both types are single-phase.



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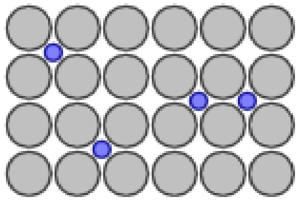

Einlagerungsmischkristalle

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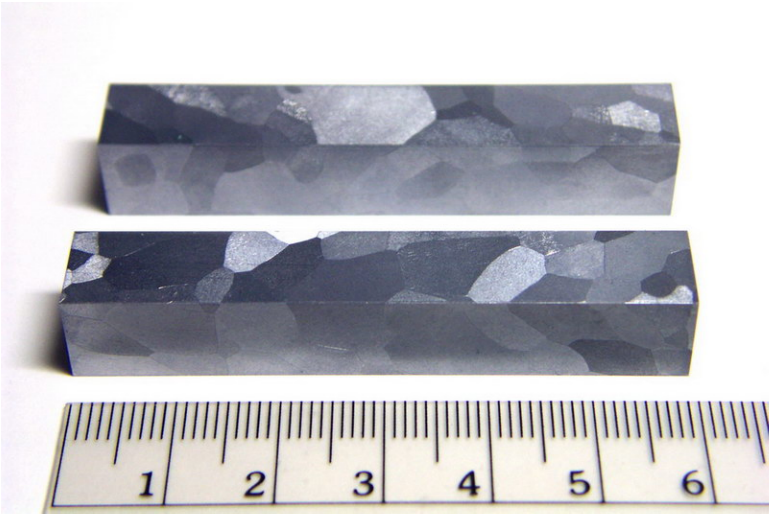
Intermetallic Phase / Intermediate Crystals

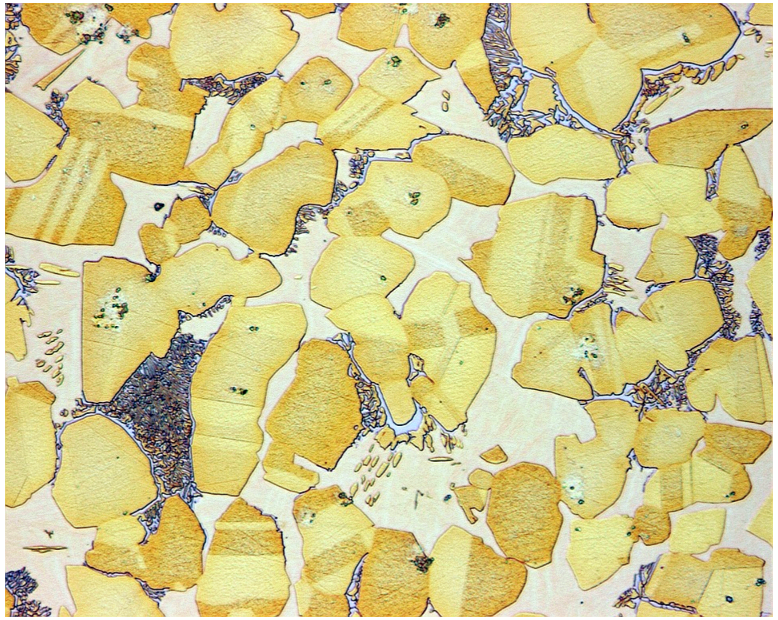
- Usually a complex lattice structure, independent of parent lattices (hundreds of atoms)
- Strong attractive forces between atom types
- In addition to metallic bonds, covalent and ionic bonds are present
  → Binding form lies between chemical and metallic → intermediate

- These are very hard and brittle
- Technical alloys usually contain less than 10% of these phases
- Important subgroup → interstitial phases (interstitial structures):
    - Carbides, borides, nitrides
    - Used in tool steels and heat-resistant steels

Microstructure of Materials

- Characterized by the type, size, shape, orientation, and arrangement of individual components (phases) such as crystallites (grains), amorphous areas, and reinforcement or filler materials





Formation of Microstructure

Melt → Cooling / Undercooling

↓

Nucleation (homogeneous + heterogeneous)

↓

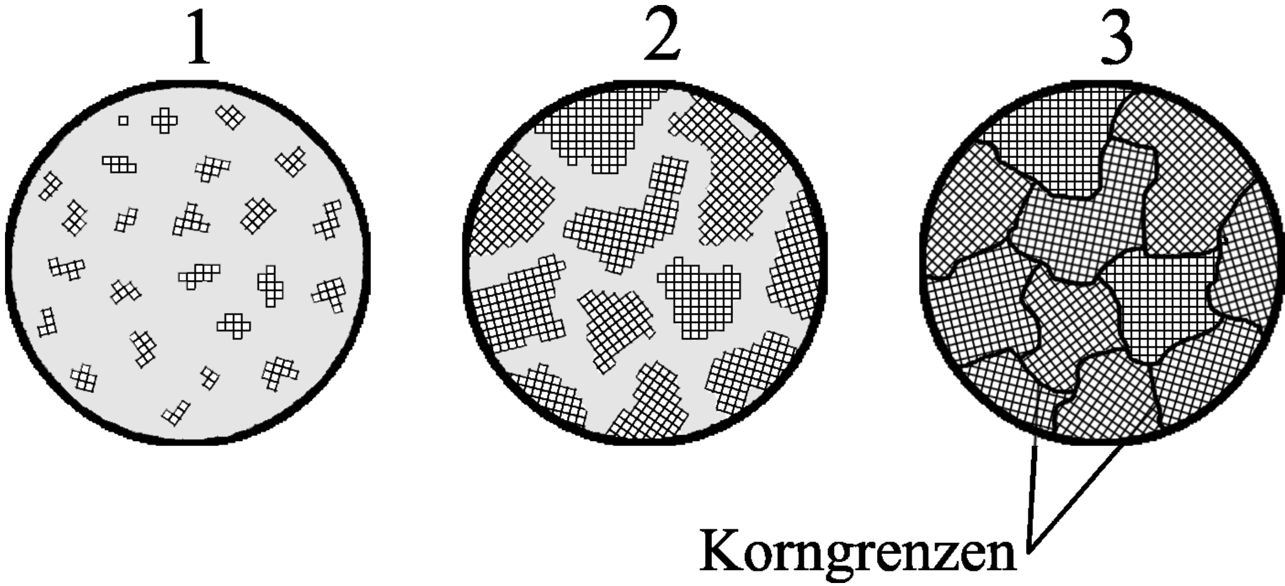
Nucleus Growth → Crystallization

↓

Formation of Crystallites (grains with grain boundaries)

↓

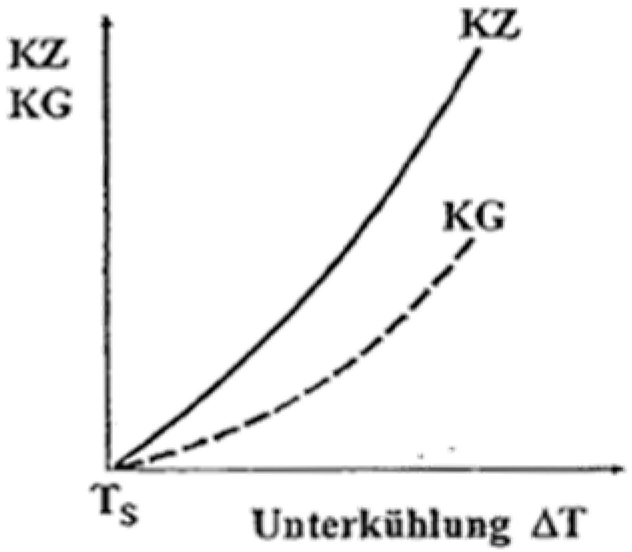
∑ of all grains and grain boundaries → Microstructure

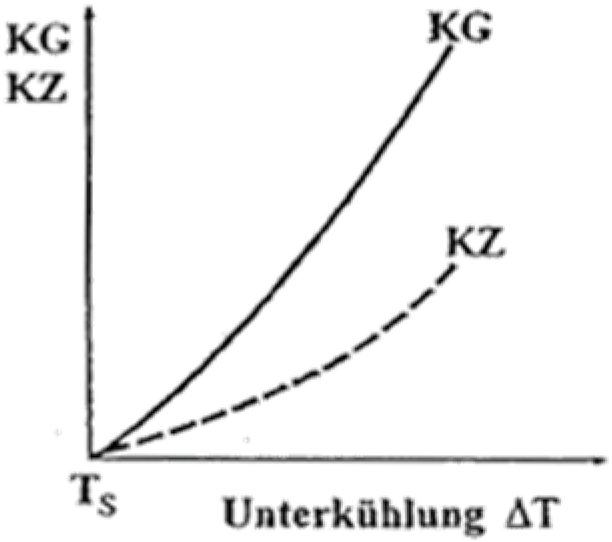


Nucleation

- Solidification does not occur uniformly → nuclei form
- Can be homogeneous (of the same type) or heterogeneous (of different types)
- Nuclei grow (crystal growth) until the entire melt has solidified
- Relationships exist between the number of nuclei (N) and the crystallization rate (R) on one hand, and the degree of undercooling ΔT on the other.

Factors Influencing Grain Size Formation





a) → Fine-grained structure

b) → Coarse-grained structure

- High number of nuclei → fine-grained structure
- Rapid crystal growth and low nucleus count → coarse-grained structure

Terminology

Grain

- Nuclei have finished growing and meet each other
- Crystal orientation between neighboring grains is generally different
- Shape and size are determined by heat flow:
  - Uniform in all directions - *globular*
  - Preferential direction of heat flow - *columnar solidification*

Grain Boundary

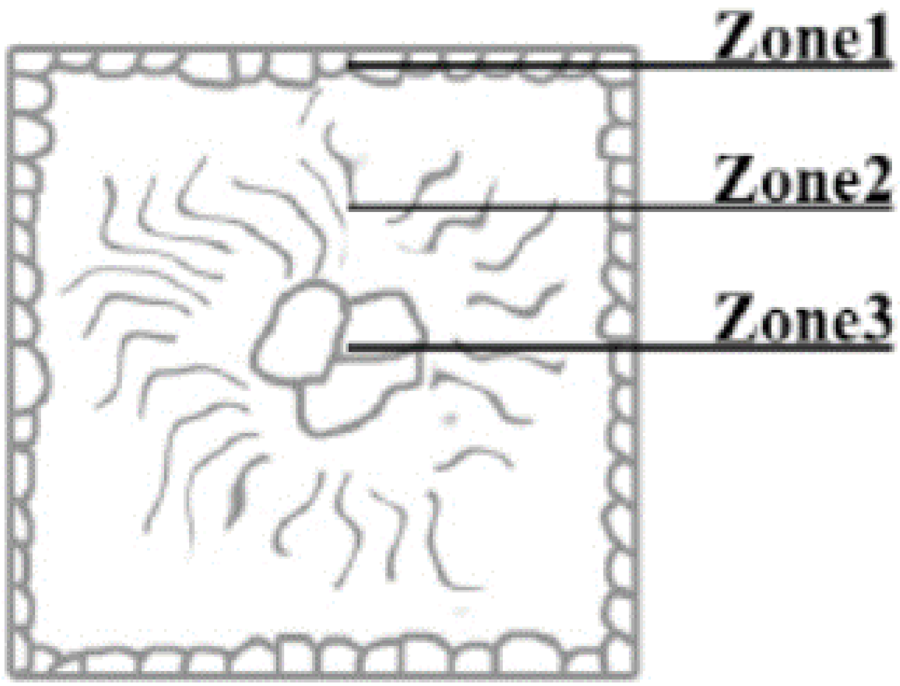
- Transition surfaces between grains

Casting or Continuous Casting

- During casting or continuous casting into a metal mold, a casting structure forms in three zones, typically with distinct boundaries:

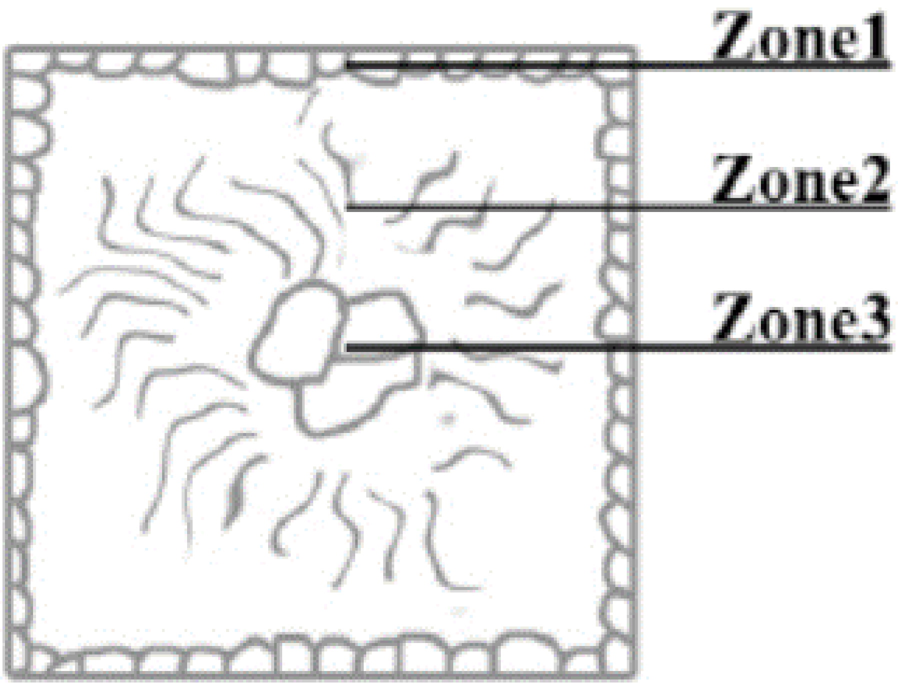
1. Fine-Grained Globular Boundary Zone

- Strong undercooling of the melt at the mold wall
- Formation of numerous nuclei → small, uniform crystallites



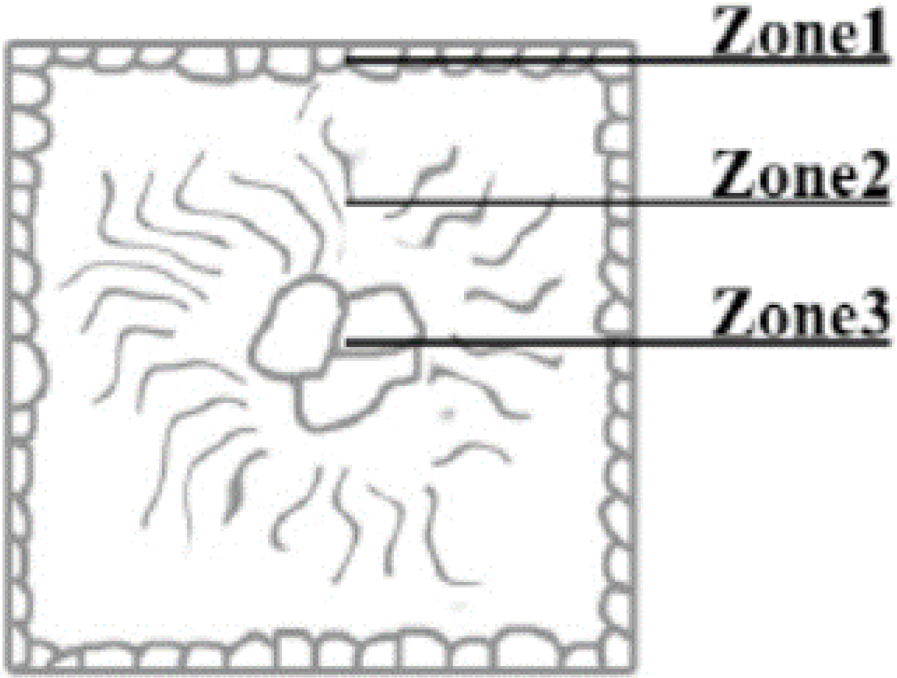
2. Columnar Zone with Stem-Shaped, Very Coarse Crystallites

- Directed growth of crystallites (stem crystals), with crystallographic orientation aligned with the direction of the heat gradient
- This orientation results in a casting texture



3. Globular Core Zone

- Impurities are pushed by stem crystals and accumulate at the core
- High number of foreign nuclei → globular fine-grained core zone
- In very pure metals, a coarse-grained structure is observed in the third zone



Microstructure Detection

- Generally, individual crystallites (grains) in a material are not visible to the naked eye.
- For materials science investigations, however, it is necessary to analyze the existing microstructure.
- Work steps:
  - targeted sample extraction
  - grinding and polishing the sample
  - etching the surface

Metallographic Sections

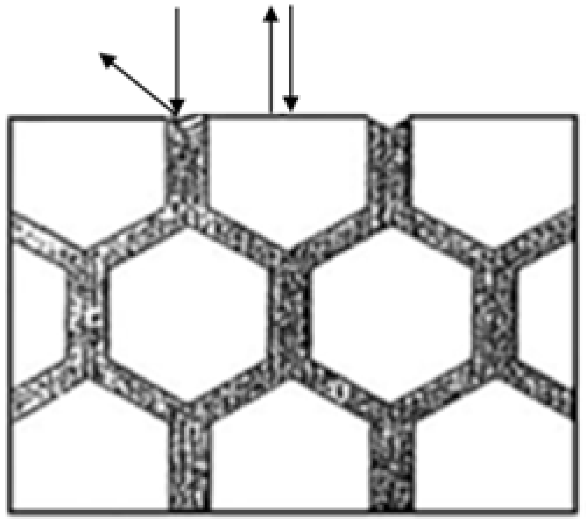
- A carefully prepared section can be viewed with a light or scanning electron microscope.
- The scanning electron microscope not only offers significantly higher resolution but also greater depth of field.

Etching

Etching for microstructure development can also be regarded as a corrosion process.

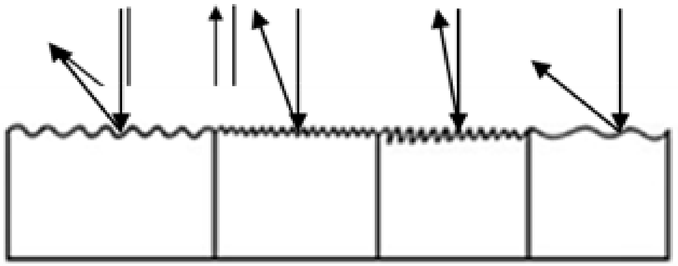
Grain boundary etching

- preferential dissolution of grain boundaries



Grain surface etching

- adjacent grain sections are roughened or covered with oxide layers to different extents
- grains reflect light differently



Macro Sections

Using macro etching, only those microstructural phenomena that are visible to the naked eye or under a magnifying glass can be studied. The following analyses are possible:

- Segregation and its localization: Heyn and Oberhoffer etching or Baumann print
- Quality of welds: Adler etching
- Development of force flow lines after plastic deformation: Fry etching

Terms for the Qualitative and Quantitative Description of Microstructures

Metallography - Metals

Ceramography - Ceramics

Plastography - Polymer materials