I. Physical metallurgy

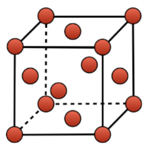
1. Classes and properties

Class	Typical properties
Metal Alloys	1) Thermal + electric conductivity 2) Ductility 3) Castable 4) Reflective
Ceramics	1) High T resistance (High E, low α) 2) High compression strength 3) Thermal + electric insulator 4) Wear resistance
Polymers	1) Cheap 2) Thermal + electric insulator 3) Corrosion resistance 4) Moldable

1.1 Structural model of metals

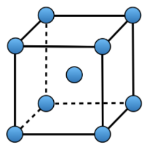
$$\phi = \frac{\text{Volume occupied by atoms in unit cell}}{\text{Total volume of unit cell}}$$

1.1.1 FCC (Face-centered cubic)



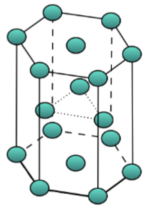
- Packing efficiency: $\phi \approx 74\%$
- Many slip systems (12)
- Closest pack direction

1.1.2 BCC (Body-centered cubic)



- Packing efficiency: $\phi \approx 68\%$
- Many slip systems (6)
- Not closest pack direction
- Cottrell atmosphere

1.1.3 HCP (Hexagonal close-packed)



- Packing efficiency: $\phi \approx 74\%$
- Very few slip systems (3)
- Closest pack direction

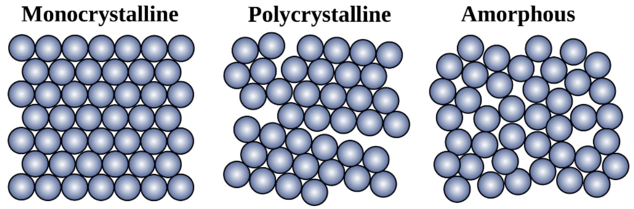
1.2 Structural model of ceramics

- Ionic bonding, complex crystal structures (ceramics), amorphous (glasses)
- Brittle, but high chemical and thermal resistance
- Insulators
- Wear-resistant (e.g. ferro-/piezoelectricity)

1.3 Structural model of polymers

- Macromolecules (10^3 to 10^5 C atoms)
- Weaker intermolecular bonds but strong atomic bond in molecular chain
- Electrically and thermally insulating
- Cheap, moldable, massive waste problem, pollutant
- Matrix for many composite materials (no recycling)

1.4 Amorphous and crystalline materials



1.4.1 Amorphous materials

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

Field: inorganic classes (also Gorilla glass), metallic glasses (ferrous transformer sheet metal), amorphous plastics (PMMA - plexiglass, COC, ...)

1.4.2 Crystalline materials

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

1.4.3 Monocrystalline materials

Only for special applications, expensive.
Field: single-crystal turbine blades (T $>$ 1000°C, creep-resistant), semiconductors, MEMS components made of silicon (gyroscopes in smartphones, accelerometers), optical elements (laser crystals, λ/4 plates, crystals for frequency doubling of lasers).

1.4.4 Polycrystalline materials

Most metal components are polycr. (made of many grains/crystals).

1.5 Directional dependence

1.5.1 Anisotropy and Isotropy

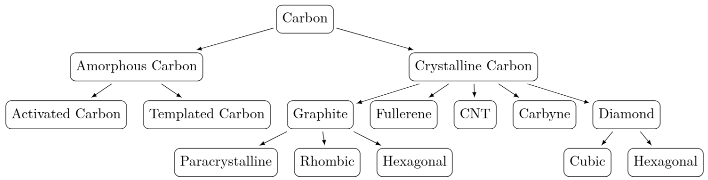
- **Anisotropic**: properties depend on the direction (eg. single crystals, wood, composites)
- **Isotropic**: properties do not depend on direction (eg. polycr. metals, amorphous materials)
- **Quasi-isotropic**: properties microscopically depend on the direction but not macroscopically

1.6 Polymorphism (Allotropy)

1.6.1 Iron

- α-Fe (ferrite, BCC) $\rightarrow$ below 911°C
- γ-Fe (austenite, FCC) $\rightarrow$ 911°Cto 1392°C
- δ-Fe (ferrite, BCC) $\rightarrow$ 1932°Cto 1536°C

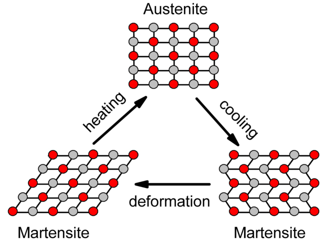
1.6.2 Carbon



1.6.3 Other materials

- Titanium: HCP $<$ 880°C, BCC $>$ 880°C
- Shape memory allory (eg. NiTi)
- Zirconia (high crack resistance due to phase transformation toughening)
- Ferro- and piezoelectric materials (eg. PZT, quartz, ...)

1.6.4 Shape memory alloy (SMA)



NiTi is a SMA used for screen lock of tablet notebooks, medtech and spectacle frames.

1.7 Microstructure and phases

1.7.1 Homogeneous microstructure

They have only one phase and crystal structure. A phase can be either crystalline or amorphous (eg. only iron crystals).

1.7.2 Heterogeneous microstructure

They have multiple phases and many types of crystal structures (eg. graphite and iron).

1.8 Alloys

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, nickel-phosphorus)

1.8.1 Microstructure of alloys

- **Solid solution crystal**: homogeneous, single-phase, only one type of crystal
- **Mix of different crystal types**: heterogeneous, multi-phase

2. Metal structures and crystal lattice defects

2.1 Lattice defects

2.1.1 0-dimensional defects

Point defects due to vacancies and impurity atoms.

2.1.2 1-dimensional defects

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

2.1.3 2-dimensional defects

Surface defects due to grain boundaries. Crystal growth starts at multiple locations within the molten metal

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 defects

Volume defects due to precipitations, inclusions, voids, cracks in the crystal structure.

3. Elastic and plastic deformation

3.1 Elastic deformation

The coefficient of thermal expansion α is inversely proportional to: Young's Modulus E, Bonding energy, Melting temp.

3.2 Elastic constants of isotropic materials

3.2.1 Elastic stress, strain, and Young's modulus

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

3.2.2 Poisson's ratio ν

When a material is stretched in x, it tends to contract in y, z:

$$\nu = -\frac{\varepsilon_{y,z}}{\varepsilon_x}$$

3.2.3 Relation between 3 isotropic elastic constants G

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

3.3 Plastic deformation in metals

The plastic deformation is permanent and non-reversible

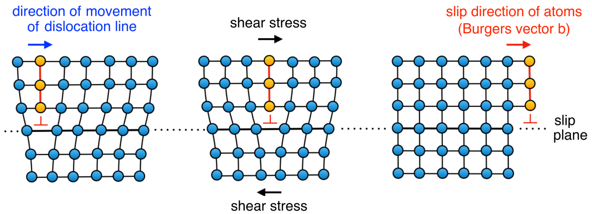
3.3.1 At room temp T_R

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

3.3.2 At high temps

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

3.4 Simplified dislocation slip model



3.5 Slip systems

3.5.1 Slip systems in FCC metals

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

3.5.2 Slip systems in HCP metals

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

3.5.3 Slip systems in BCC metals

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

3.6 Metals crystal structure vs 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)

3.7 Cottrell atmospheres and Dislocation pinning

- In α-Fe with a BCC structure (ferrite), the sites for interstitial atoms are much smaller than γ-Fe (austenite)
- Carbon atmos in ferrite diffuse into the distortion fields near dislocation lines, forming Cottrell atmospheres
- Causes upper yield point (R_{eH}) in tensile tests and brittle fracture at low temps
- During plastic deformation, dislocations must first break freefrom the Cottrell atmosphere.

4. Strenghtening mechanisms

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

4.1 Solid-solution hardening

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

4.1.1 0-d: SSH application field

Al-Mb and Al-Mg alloys (5000 and 3000) for automotive sheet metal, airplane outer skin, beverage cans; Structural and stainless steels; Gold jewerly (Au with Ag, Cu, Ni, Pt, Pd, ...)

4.2 1-d: Strain hardening (Work hardening)

- Cold work increases dislocation density $\rightarrow$ dislocation entanglement
- Cold working / cold forming: below the recrystallization temp
- Hot forming: above the recrystallization temp
- Recrystallization temp: $(T_{\text{recr}} \approx 0.4, T_m\ [\text{K}])$
- **Result**: strength increases but ductility decreases

4.2.1 SH application field

Any cold-formed parts: cold rolled sheet metal, neckline holes in sheet metal of a washing machine drum, cold pressed steels.

4.3 2-d: Grain boundary hardening

- Smaller grains increase strength: grain boundaries hinder dislocation slip
- Not suitable at high temp: grain growth reduces strength and ductility
- **Result**: strength and ductility both increased (statistical grain orientation, Schmid's law)

4.3.1 GBH application field

High-strength fine-grain or even Q+T structural steels: cranes, oil platforms, bridges, shipbuilding.

4.4 3-d: Precipitation hardening

- Increase in strength by coherence of the precipitates and size and number of the precipitates
- **Result**: increase in strength but decrease in ductility

4.4.1 Effect of precipitate coherence on strength

Coherent: lattice planes match, strong strain fields in the matrix $\rightarrow$ large strength increase.

Semi-coherent: misfit dislocations at the interface reduce lattice strain $\rightarrow$ strength decreases.

Incoherent: lattice planes mismatch; little matrix distortion $\rightarrow$ small strength increase.

4.4.2 PH application field

High-strength aluminum alloys for aerospace, maraging steels, stainless PH steels, highly temp-resistant Ni base superalloys for turbine blades.

II. Strength and Ductility

5. Properties of material

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

5.1 Failure hypotesis and Material testing methods

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

6. Tensile test

6.1 Engineering stress and stress conditions

6.1.1 Normal vs Engineering vs Shear stress

Engineering stress is the force F acting on the original cross-sectional area S_0. Normal stress is the normal force F_N that acts perpendicularly to S_0. The shear stress τ is the force F_Q parallel to S_0.

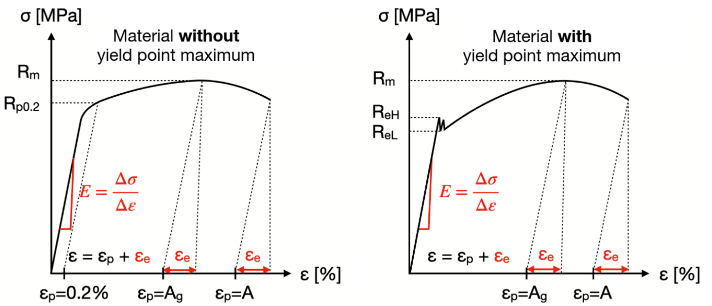
$$\sigma = \frac{F}{S_0} \quad ; \quad \sigma_N = \frac{F_N}{S_0} \quad ; \quad \tau = \frac{F_Q}{S_0} \quad ; \quad \sigma = E \cdot \varepsilon$$

6.1.2 Engineering strain ε

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

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

6.2 Stress-strain behavior of metals



6.2.1 Yield stress R

- **R_{eH}**: Upper Yield point
- **$R_{p0.2}$**: 0.2% Yield Stress
- Without max yield point: σ_{max} = $R_{p0.2}$

6.2.2 Yound's modulus

Slope of the linear-elastic region:

$$E = \frac{\Delta\sigma}{\Delta\varepsilon}$$

6.2.3 Tensile strength R_m

It correspondes to the stress at the max of the stress-strain curve. With max yield point: σ_{max} = R_m; upper yield point R_{eH}.

6.3 Fracture strain A

Plastic strain at fracture is defined with respect to the initial specimen length L_0. (eg. $L_0 = 50\text{mm} \rightarrow A_{50\text{mm}}$)

6.3.1 Uniform strain A_g

It corresponds to the plastic strain at maximum load before necking begins.

6.3.2 Contraction at fracture Z

$$Z = \frac{\Delta S}{S_0}$$

7. Other quasi-static mechanical tests

7.1 Bending test

A specimen is placed on two supports, loaded in bending (typically at midspan) until failure, and the maximum bending stress is calculated.

7.2 Torsion test

A cylindrical specimen is clamped and twisted by applying torque until yielding or fracture, and the torsion strength is taken from the peripheral shear stress.

7.3 Creep and relaxation tests (High temps)

- Creep: time-dependent deformation under constant stress
- Relaxation: decreasing stress under constant strain
- At high T, strength becomes time- and strain-rate-dependent
- Strain changes with time under constant load
- Creep/relaxation tests assess heat-resistant materials for high-T applications (eg. steels and Ni alloys above 400°C)

III. Steel - technology and applications

Steel is a Carbon-iron alloy. Has very good properties: strength, ductility, toughness, formability, machining, weldability. Can be heat-treated due its polymorphism.

8. Steel Technology

8.1 Blast furnace and Pig iron

- **Process**: reduction of iron oxide with coke
  $Fe_2O_3 + 3C \rightarrow 2Fe + 3CO$
- **Product**: pig iron (3-5% C, also Mn, Si, S, P)

8.2 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

8.3 Secondary metallurgy

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

8.4 Semi-finished products

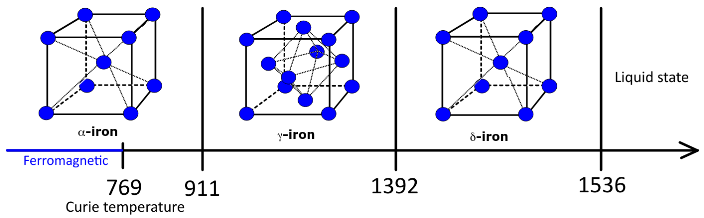
- Produced mainly by continuous casting (slabs, billets)
- Formed into sheets, plates, wires, rods, pipes, and profiles by hot or cold rolling/drawing

8.5 Important alloying elements

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
Wear/heat resistance	Cr (>1%), Mo, V, Al, Ti, Nb, Mo
Scale resistance	Cr, Al, Si

9. Microstructure formation

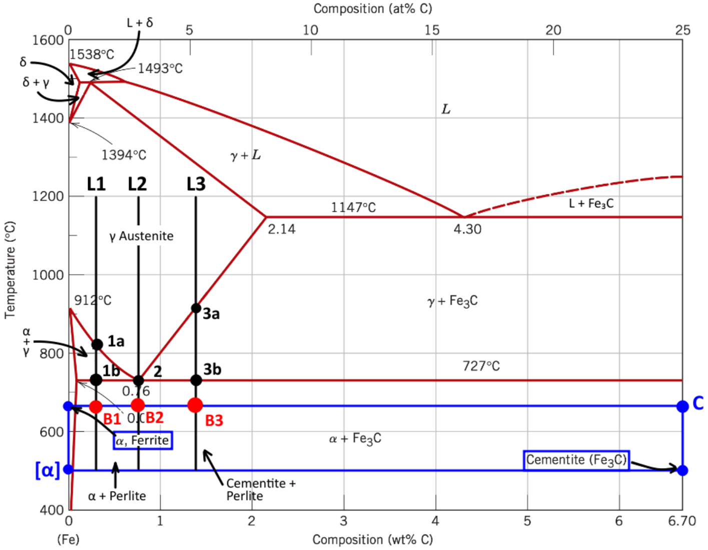
9.1 Polymorphism of iron



9.2 Metastable iron-iron carbide phase diagram

9.2.1 Phase diagram

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



9.3 Microstructure formation of Steel (Slow Cooling)

Hypoeutectoid	< 0.8	Primary ferrite +pearlite	ductility ↑↑ weldability ↑↑ formability ↑↑ hardness ↓
Eutectoid	0.8	Pearlite (ferrite +cementite)	hardness ↑ toughness ↑ ductility ↓
Hypereutectoid	> 0.8	Primary cementite +pearlite	hardness ↑↑ wear ↑↑ toughness ↓

9.3.1 Eutectoid steel final microstructure at T_R

The microstructure is 100% pearlite, consisting of ferrite lamellae (soft, ductile phase forming the light layers), and cementite lamellae (hard, brittle phase forming the dark layers).

9.3.2 Hypereutectoid steel final microstructure at T_R

Final components are grain boundary cementite (hard and brittle, formed before eutectoid reaction) and pearlite (lamellar mixture of ferrite and cementite).

9.4 Faster cooling / Quenching

Fast cooling of steels changes the transformation behavior compared to equilibrium cooling.

9.4.1 Fast cooling

- Transformation temps shift to lower values
- Pearlite become finer and forms over a wider Temp range
- Martensite and bainite can form

9.5 Ferrite

- α-iron (BCC), stable at low temps
- Very low carbon solubility → carbon tends to form cementite
- Soft and ductile → good formability and toughness

9.6 Austenite

- γ-iron (FCC), stable at higher temps
- High carbon solubility → carbon dissolves readily
- Parent phase for transf. to pearlite, bainite, and martensite

9.7 Pearlite

- Forms from austenite during slow cooling (eutectoid trans.)
- Lamellar mixture of ferrite (α) and cementite (Fe_3C)
- Higher strength and hardness than ferrite, but lower ductility; finer lamellae give higher strength

9.8 Martensite

- Very fast cooling of austenite produces martensite
- Diffusion does not occur, so no ferrite or pearlite
- Lattice shear of FCC austenite produces BCT

9.9 Bainite

- Produced by a rapid cooling (250-500°C)
- Combined shear and limited diffusion; cementite precipitate
- Higher strength than pearlite, more ductile than martensite
- Good for high-performance components and tools

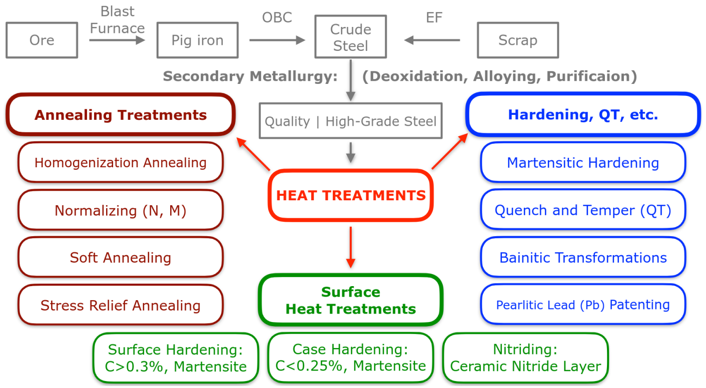
9.9.1 Upper bainite

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

9.9.2 Lower bainite

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

10. Heat treatments



10.1 Process steps

Process step	Microstructure after each process step	Strength and toughness after each process step
Austenitizing	Austenite	Low strength (low $R_{p0.2}$), high toughness, high energy absorbed.
Quenching	Martensite	Very high strength, brittle.
Tempterting 400-700°C	Very small ferrite and cementite crystals	High strength, high toughness.

10.2 Homogeneization annealing

- Elimination of segretations
- Often performed together with hot forming

10.3 Normalizing

10.3.1 Austenization + slow cooling

- Produces a uniform, fine-grained microstructure
- Austenitize: transform ferrite to austenite
- Slow, controlled cooling
- **Result**: fine grains → higher strength and toughness

10.4 Martensitic hardening and Q+T

10.4.1 Martensitic hardening

Austenitize → quench → low-temp temper (200°C)

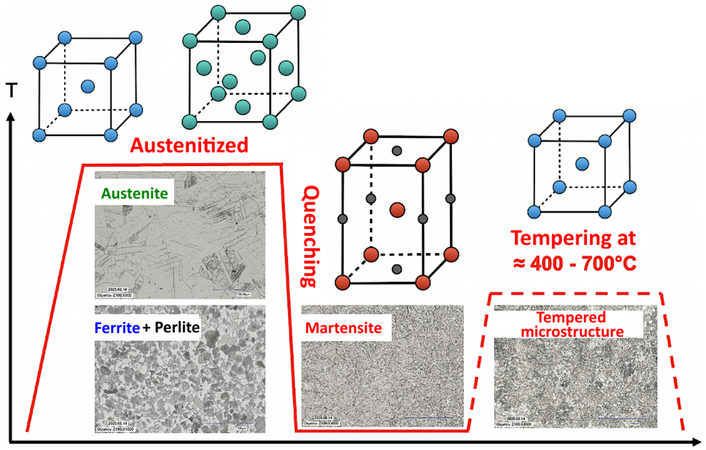
10.4.2 Quench + temper

Austenitize → quench → temper (350-700°C) → tempered martensite

10.4.3 Bainitic transformation

Continuous cooling of low-alloy steels to form bainite.

10.4.4 Graphical representation



10.5 Case hardenable steels

Typically contain less than 0.25% carbon before carburizing. After case hardening and quenching, martensite forms at the surface, improving wear resistance and fatigue resistance.

11. Hardening of the surface overview

11.1 Without thermochemical diffusion

11.1.1 Surface hardening

For C > 0.3%, quenching forms martensite at the surface.

11.2 With thermochemical diffusion

11.2.1 Case hardening

For C < 0.25%, first diffuse C (carburizing) or C+N (carbonitriding), then quench to form surface martensite.

11.2.2 Nitriding

Diffuses N to form a hard nitride layer (or carbonitrades in nitrocarburizing). In works for any steel, highest hardness in nitriding steels with Al/Mo/C.

11.3 Hardening Depth

- **SHD**: at $0.8 \cdot HV_{surface}$ (80% of SH)
- **CHD**: at 550 HV1 (limit hardness line at 550 with HV1 load)
- **NHD**: at $HV_{lower\ line}$ + 50HV0.5

IV. Hardness and Toughness

12. Hardness

It measures resistance against localized plastic deformation.

12.1 Hardness testing

Testing method	Application
Vickers (HV)	Universal application
Rockwell (HCR)	For hard steels
Brinell (HB)	For soft steels and aluminum
Berkovich	For nanoindentation
Shore A, D	For rubber and plastic

12.2 Hardness Testing procedures

12.2.1 Indentation depth

Hardness is based on the indenter penetration depth.

12.2.2 Indentation area

Hardness is based on the indentation surface area.

13. Notch Impact Toughness

13.1 Impact Notch Toughness test (Charpy)

- Applied mainly to structural steel (BCC)
- Shows the transition temp from ductile to brittle fracture
- Determines the absorbed impact energy ("notch toughness")
- Failure hypotesis: crack propagation under sudden loads

13.2 Toughness

13.2.1 Material behavior

- **Tough material**: absorb high energy before fracture
- **Brittle material**: fracture with little energy absorbtion

13.2.2 Energy criterion

- **Ductile fracture**: if absorbes > 27 J of the impact energy
- **Brittle fracture**: if absorbes < 27 J of the impact energy

13.2.3 Stress State dependence

- Monoaxial (tensile test): material can yield in lateral ways
- Biaxial (pressure vessels): yield possible in one direction
- Triaxial (notches): no yielding possible, leads to brittle failure

13.3 BCC brittle behavior at low temps

13.3.1 Cottrell atmosphere (BCC α-Fe)

Small interstitial sites, C/N diffuse to dislocation stress fields and cluster there, forming atmospheres that lock dislocations.

13.3.2 Dislocation pinning

Cottrell locking produces an upper yield point R_{eH}, plastic flow starts only after dislocations break away.

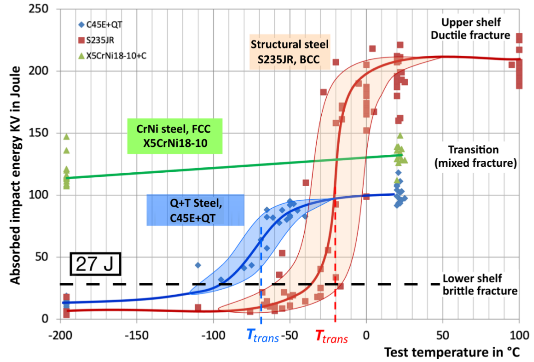
13.3.3 Low temperature brittleness (BCC)

At low temp or high strain rate, breakaway is difficult
$\rightarrow$ stronger pinning, reduced ductility, and brittle behavior.

13.3.4 Absorbed Notch Impact energy

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

13.4 Absorbed energy - Temperature graph



V. Aluminum - Wrought and Cast alloys

14. Properties and application of aluminum alloys

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

15. Designation of alloys and conditional designations

15.1 Numerical Designation System (DIN EN 573-1)

EN AW-: Wrought alloys

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

EN AW-: Cast alloys

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

15.2 Condition Designation (DIN EN 515)

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

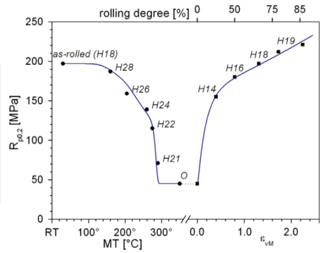
Hxx	Meaning
Hx1	1/8-hard
Hx2	1/4-hard
Hx4	1/2-hard
Hx6	3/4-hard
Hx8	hard
Hx9	extra hard (Hx8 + 14 MPa)

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

15.3 Cold-working H

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

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



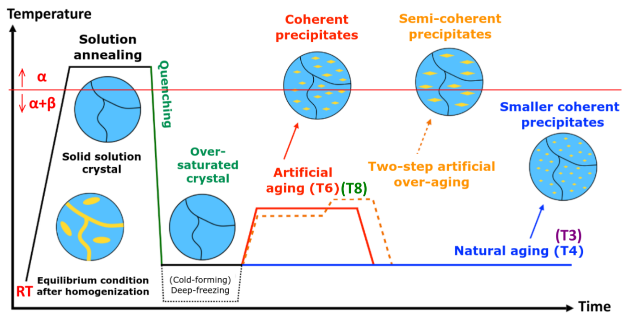
15.4 Precipitation hardening (age hardening)

15.4.1 Age hardening steps

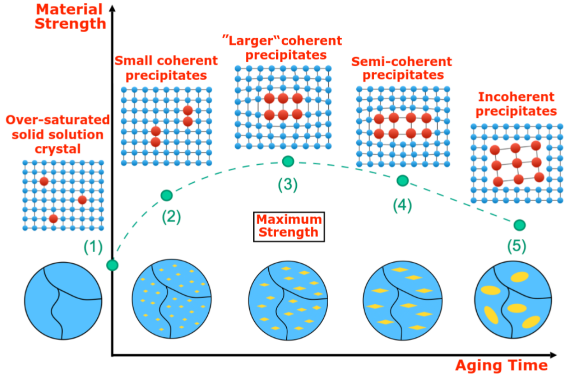
1. Solution annealing (W): dissolves existing precipitates into alloy
2. Quenching: rapidly cools to form a supersaturated solid solution without precipitates
3. Aging: small, coherent precipitates form, alloy strengthening

15.4.2 Aging types

- Natural aging: at room temps, moderate strength, lower hardness, higher ductility
- Artificial aging: elevated temps (120-200°C), higher strength and hardness, lower ductility



15.4.3 Artificial aging



16. Aluminum Wrought Alloys

16.1 Pure aluminum

16.1.1 Properties

- Excellent electrical conductivity (best weight/cost balance)
- High thermal conductivity (good heat dissipation)
- Good corrosion resistance, formability, and weldability
- Low inherent strength; strengthened by cold working and grain refinement
- Very suitable for surface finishing/polishing/anodizing

16.1.2 Applications

- Electrical/electronics (busbars, bonding wires, HV cables)
- Heat exchangers/heat sinks; avoid Al-Cu contact to limit galvanic corrosion
- Corrosion-resistant cladding on high-strength sheets for aircraft/automotive
- Food packaging (foils, dishes, coffee capsules)

16.2 Type of wrought alloys system

16.2.1 EN AW-3XXX: (Al-Si)

- Stronger than pure Al, easy to form/weld
- Good corrosion resistance
- Tanks/chemical equipment, cookware, gas pipes

16.2.2 EN AW-4XXX: Al-Si

- Mainly used as cast alloys/coating
- Low eutectic melting point
- Cast parts, corrosion-resistant coatings, welding wires

16.2.3 EN AW-5XXX: Al-Mg

- Excellent weldability and corrosion resistance
- Ship hulls, tanks, cookware, beverage can lids

16.2.4 Over-saturated 5XXX (>3% Mg, quenched)

- High strength
- Risk of intergranular corrosion and stress-corrosion cracking
- High-strength rods/profiles, avoid hot/chloride exposure

16.2.5 EN AW-6XXX: Al-Mg-Si

- Good strength, good processing properties
- Formability + weldability + corrosion resistance + anodizing
- Extruded profiles, doors/windows, bicycle frames

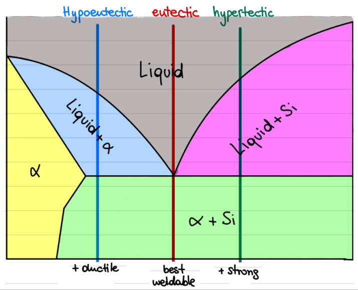
16.2.6 EN AW-2XXX: Al-Cu

- High strength and fatigue performance (T3/T4/T6)
- Poor fusion weldability and corrosion resistance
- Aircraft, high-strength structural parts

16.2.7 EN AW-7XXX: Al-Zn-Mg (-Cu)

- Very high strength; poor corrosion resistance and weldability
- SCC/exfolian risk: often use over-aged tempers
- Aircraft parts, climbing hardware, lightweight housing

17. Aluminum cast alloys



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

17.1 Hypoeutectic cast alloys

- Solidify as primary α-Al + remaining eutectic
- At T_R: primary α-Al crystal + residual eutectic
- Mg/Cu/Fe additions allow precipitation hardening of α
- Typical alloys: EC AC-465000, EC AC-42000, EN AC-435000
- Uses: EV motor housing, chassis parts

17.2 Eutectic cast alloys

- Lowest melting point: excellent castability, no freezing range
- Na/Sr modify and refine eutectic; Ti/TiB_2 suppress Si needles
- Typical alloys: EN AC-44100, EN AC-44300, EC AC-47000
- Uses: ribbed casting, pump/engine housing, cylinder heads

17.3 Hypereutectic cast alloys

- Primary Si crystal: very high wear resistance and reduced thermal expansion
- Uses: pistons (eg. EN AC-48000 (T6))

18. Surface technology - corrosion protection

18.1 Natural oxide layer on aluminum

- Aluminum forms an immediate, compact Al_2O_3 oxide layer (passivation)
- Properties: hard (ceramic), corrosion-resistant, stable at pH 5-8, only a few nm thick
- Thickening: chemical (chromating/chromitizing, boiling water) or electrochemical (anodizing)

18.2 Chemical conversion coatings

- Remove the natural oxide by pickling/etching, then convert the surface into a thin conversion layer (oxide/chromate/chromite/phosphate)
- Coating is very thin, may show microcracks
- CCC (chromate, Cr VI): transparent/yellow/blue; good paint/primer adhesion; alternatives use Cr III (chromitizing) or chromous-acid systems
- Phosphating: phosphoric-acid based; adhesion primer for paint; common in the food industry

18.3 Electrochemical anodizing

- GS (sulfuric gas): oxide up to 30μm; mainly decodative
- GSX (sulfuric + oxalic): 80-150μm; very good wear protection
- CAA (chromic acid): thin. flexible, low-crack layer; very high corrosion resistance; mainly aerospace (Cr(VI) hazard)
- TSA (tartaric-sulfuric): safer, more environmentally friendly

VI. Non-ferrous metals and applications

19. Titanium and Titanium alloys

19.1 Key properties of pure Ti

- $E \approx 110$ GPa (low compared to steel)
- Very good corrosion resistance, very good biocompatibility
- Interstitial (O, Fe) high strength but low ductility

19.2 Crystal structure/polymorphism

- α-Ti ar T_R; β-Ti above 882°C
- Hot-forming easier in β; cold-forming limited in α
- Service temperature limited by phase changes

19.3 Alloy types

- c.p. Ti: best corrosion + weldability, lower strength
- α alloys: solid-solution strengthened, not precip.-hardenable
- $\alpha + \beta$ alloys: best all-round, heat-treatable
- β alloys: highest strength, usually lower corrosion resistance

19.4 Application

- Aerospace/structures and landing-gear parts
- Chemical industry: heat exchangers, pipes, pumps/valves
- Medical: implants and instruments

20. Magnesium and Magnesium alloys

20.1 Key properties of pure Mg

- Very low density

- HCP structure; very low stiffness. $E \approx 44$ GPa
- Very un-noble, corrosion sensitive

20.2 Main limitations
- Low strength; low fatigue/wear/creep resistance
- HCP: few slip systems $\rightarrow$ limited cold-formability
- Machining risk: chips/dust can ignite

20.3 Alloy types
- Mg-Al-Zn: common low-cost cast alloys
- AMZ40: 4% Al + minor Mn/Zn (die-cast parts)
- Rare-earth cast alloys: improved high-T/creep performance

20.4 Application
- Automotive die-cast parts: brackets, steering
- Lightweight housing: laptops, cameras
- Aerospace casting: very light gearbox housings

21. Nickel and Nickel alloys

21.1 Key properties of pure Ni
- FCC crystal structure: very ductile even at low temps
- Self-passivating: very good corrosion resistance
- High melting point: good high-temps capability
- If precipitation-hardened: higher strength, creep resistance

21.2 Alloy families
- Ni-Cu: solid-solution strengthened; very corrosion resistant
- Ni-base superalloys: high-temp + oxidation/corrosion
- Soft-magnetic Ni: very high permeability, magnetic losses
- NiTi: superelasticity + shape-memory effect

21.3 Applications
- Corrosive environment: seawater, chemical plants
- High-temp parts: gas turbines, furnaces
- Electrical / magnetic: coil cores, sensors
- Medical: stents, orthodontic wires

22. Copper and Copper alloys

22.1 Key properties of pure Cu
- Very high electrical and thermal conductivity
- Medium strength, high ductility
- FCC: very well cold-formable (malleable/ductile)
- Good atmospheric corrosion resistance

22.2 Refining / purity
- Conductivity requires very high purity
- Industrial route: fire refining then electrolytic refining
- Cu dissolves at anode and re-deposits at cathode

22.3 Alloying and applications
- Alloying: $\uparrow$ strength but $\downarrow$ el + therm conductivity
- Pure Cu: cables, wires, busbars
- Low-alloy Cu: overhead contact lines, spring contacts
- Brass (Cu-Zn): good formability + machinability
- Bronze (Cu-Sn): springs, wear-resistant parts

23. Zinc and Tin

23.1 Key properties
- Zn (pure): sacrificial corrosion protection for steel; cheap, easy to cast
- Sn: corrosion-resistand and food-safe

23.2 Crystal structure / formability
- Zn: HCP; at TR already hot-forming, deformation
- Sn: low melting point: hot-formable already near TR

23.3 Applications
- Zn: galvanizing, die casting, alloying element for brass
- Sn: tin plating for food and beverage, electronics solders

24. Refractory metals (W, Mo, Ta, Mb)

24.1 Key properties
- Very high melting temp: high-T capability, bus expensive
- Very good thermal and chemical/corrosion resistance
- High stiffness; generally low thermal expansion

24.2 Crystal structure and deformation behavior
- BCC lattice: brittle-ductile transition temperature
- W, Mo: often brittle at TR; become ductile at higher T
- Ta, Nb: already ductile at TR

24.3 Strengthening concept
- Strength at high T increases mainly by SSH
- Grain boundaries can limit creep/ductility at high T

24.4 Applications
- W: TIG welding electrodes, high-T components
- Mo: high-T parts, air-lubricated bearing components
- Ta: chemical/biomedical components, Ta capacitors
- Nb: high-T/corrosion-resistant components, aerospace

25. Precious metals (Pt, Pd, Au, Ag, Ir, Rh)

25.1 Key properties
- Very noble: high corrosion/oxidation resistance; stable in air
- High value: often used as thin layers
- Often excellent catalysts

25.2 Jewelry alloys
- Platinum: typical fineness 950, 900, 800
- Gold: common fineness 999, 750, 585, 375
- Silver: sterling 925

25.3 Applications
- Pt/Pd/Rh: Catalysts, chemical process
- Au: conductors, contact layers, wire bonding
- Rh: watch and jewelry industry
- Au/Ag/Pt/Pd: finance and investment speculation

VII. Corrosion and corrosion prevention

26. Corrosion

26.1 Electrochemical corrosion of metals
- Indirect redox: oxidation at the anode + reduction at the cathode, coupled by an electron current
- Requirements: less noble anode, more noble cathode, electrical connection, electrolyte

26.2 Galvanic cells
- Two galvanic half-cells form a galvanic element; corrosion is driven by potential diff. and/or ion concentration diff.
- Electrode potential at one interface is not measured directly; measure voltage between two half-cells
- Standard hydrogen electrode: 1 atm, pH = 0, 25°C, E° = 0 V

26.2.1 Chemical reactions
Anode/Oxidation: $Zn \rightarrow Zn^{2+} + 2e^-$
Cathode/Reduction: $Cu^{2+} + 2e^- \rightarrow Cu$
Note: noble metals are never the cathodes!

26.3 Oxygen and hydrogen corrosion
- Anode: usually the least noble metal/phase in the system
- Cathode at neutral/basic pH: oxygen electrode
- Cathode at pH < 5 or with chlorides: hydrogen electrode

26.3.1 Oxygen corrosion
Anode: $Fe \rightarrow Fe^{2+} + 2e^-$; $2Fe \rightarrow 2Fe^{2+} + 4e^-$
Cathode: $H_2O + \frac{1}{2}O_2 + 2e^- \rightarrow 2OH^-$; $2H_2O + O_2 + 4e^- \rightarrow 4OH^-$

26.3.2 Hydrogen corrosion
Anode: $Fe \rightarrow Fe^{2+} + 2e^-$
Cathode: $2H^+ + 2e^- \rightarrow H_2$

26.4 Passivation
- Some metals form a dense oxide layer that slows corrosion
- Stainless steel: passivation needs about $\geq$ 10.5-12% Cr; layer is very thin and self-renewing
- Al/Ti/Zn oxides are more insulating; passivation can increase risk of localized attack (pitting)

26.5 Area rule
- Small anode + large cathode $\rightarrow$ high corrosion rate
- Large anode + small cathode $\rightarrow$ low corrosion rate

27. Types of corrosion

27.1 Surface corrosion
- Relatively uniform material loss over large areas
- Typical for steels in atmospheric exposure
- Main risk: loss of cross-section: reduced load capacity

27.2 Contact corrosion / Selective corrosion
- Contact corrosion: dissimilar metals connected + electrolyte $\rightarrow$ less noble dissolves; noble surface acts cathodically
- Severity strongly depends on area ratio
- Selective: in multiphase alloy the less noble phase corrodes

27.3 Pitting corrosion (PREN)

- Local breakdown of passivation: tiny anode + no repassivation inside the pit
- Chlorides concentrate: self-accelerating, acidifies in the pit
- Higher PREN, better pitting resistance:
  - PREN > 32: seawater resistant
  - PREN > 17: often acceptable for medtech/watches
- Mo increases corrosion resistance and sweat resistance

27.4 Intercrystalline corrosion (IC)

- Sensitization in stainless steels: Cr carbides at grain boundaries $\rightarrow$ no local repassivation
- Prevention: low C grades (<0.03%), Ti/Nb stabilized grades, or solution anneal + rapid cooling
- Strength ↑: C↓, Ti↑, Nb↑, Ta↑, TiC↓

27.5 Crevice corrosion

- Like pitting, but driven by oxygen depletion in a crevice
- Non-aerated zone becomes anodic; chloride enrichment is typical; avoid/seal crevices

27.6 Stress corrosion cracking (SCC)

- 3 factors: susceptible material; specific medium; tensile stress
- Countermeasures: reduce stress, change environment, change materials, coatings/cathodic protection

28. Corrosion prevention

28.1 Active

- Sacrifical anode/coating with a less noble metal (Zn,Al,Mg) to protect steel
- Impressed current cathodic protection (external DC source), requires an electrolyte path

28.2 Passive

- Barrier layers: paints, varnish, plastics, oils; oxides, phosphates, enamel; noble metal coatings (Ni,Au)
- Design/material measures: avoid crevices/water traps/sharp edges, electrically insulate dissimilar metals, improve surface quality

VIII. Ceramic and glasses

29. Ceramics

29.1 Properties and applications of ceramics

Pros: Heat resistance, hard/wear resistance, high compression strength, high Young's Modulus E, low thermal expansion coefficient, foot safe, insulator (most ceramics)
Cons: Brittle, crack formations, not tensile, cost
Appl.: Bearings, construction materials, coatings, medtech

29.2 Bonding and structure

- Mostly ionic/covalent bonding (eg. oxides, nitrides, carbides, borides)
- Ceramics have crystalline structure

29.3 Processing route

Powder production $\rightarrow$ shaping (pressing/extrusion/injection) $\rightarrow$ debinding $\rightarrow$ sintering (shrinkage + densification) $\rightarrow$ finishing (grinding/polishing).

29.4 Brittle fracture

- Strength controlled by defects (pores/cracks): "weakest link" behavior, crack initiation often at surface/defects
- Size effect: larger volume $\rightarrow$ higher defect probability $\rightarrow$ lower fracture strength

29.5 Weibull distribution

- As for brittle fracture, size effect also for Weibull
- Higher Weibull modulus $m \rightarrow$ less scatter (best quality)
- Depends on the material composition (purity), grain size, porosity, volume, and manufacturing process
- Large $m \rightarrow$ narrow fracture strength distribution $\rightarrow$ good microstructure quality

29.6 Fracture toughness K_{Ic}

$$K_{Ic} = f\sigma_c\sqrt{\pi a}$$

a = crack size, σ_c = fracture stress, f = geometry factor

- K_{Ic}: critical mode-I stress intensity (crack becomes unstable $\rightarrow$ brittle fracture)
- Higher K_{Ic}: more crack tolerance
- Ceramics: measured often in notched bendings

29.7 Ceramic classes

29.7.1 Classic ceramics (silicate or natural)

- Raw materials: kaolin + quartz + feldspar
- Cordierite: low coefficient of thermal expansion and good thermal shock resistance
- Stearite: ten times lower dielectric loss factor tan δ compared to electroporcelain
- Products: porcelain, stoneware, sanitary
- Glazes reduce open porosity
- Applications: sanitary ceramics, dishes, construction

29.7.2 Refractory ceramics

- High-T linings for furnaces/steel
- Chamotte: for heat treatment ovens
- Magnesia: for fireproof refractory stones in steel ladles
- May show softening interval due to mixed phases

29.7.3 High-performance (technical) ceramics

- Chemically processed raw materials
- Additives (binders) as raw materials are not moldable
- Oxide cemarics, non-oxide ceramics
- Applications: technical products (high-tech)

29.8 Structural high-performance ceramics

29.8.1 Alumina (Al_2O_3)

- Increase of E and strength with degree of purity
- Hard, wear resistant, good electrical insulator, corrosion resistant
- Applications: insulators, melting pot, abrasive powder
- Single crystalline (sapphine): transparent, scratch-resistant, thermoshock resistant. For watch glasses

29.8.2 Zirconia (ZrO_2, stabilized)

- Higher fracture toughness K_{Ic}; increases in partially stabilized
- Polymorphism: stabilized (Y_2O_3/MgO/CaO) controls phases
- Can conduct oxygen ions (sensor applications)
- Applications: forming tools, knives, implants

29.8.3 Silicon carbide (SiC)

- Very hard, high thermal conductivity, low thermal expansion
- High temperature and wear resistance
- Applications: bearings, fireproof ceramics, heating elements

29.8.4 Silicon nitride (Si_3N_4)

- Improved toughness via microstructure (crack deflection)
- Good wear and temeprature resistance
- Applications: pipes, molds, wire production

29.9 Functional ceramics

29.9.1 Piezoelectric ceramics

- Require non-centrosymmetric structure
- Piezo effect disappears above Curie temperature
- Applications: sensors/actuators

29.9.2 Ferrites

Soft magnetic ceramics (eg. induction applications)

29.9.3 Superconducting ceramics

- High critical temp relative to metallic superconductors (eg. Al, Pb, Nb_3Sn, NbTi, MgB_2)
- Enables liquid nitrogen cooling (77K) for strong-field appl.
- Uses: magnetic resonance imaging, strong magnetic fields

29.9.4 Optical ceramics

Single crystal ceramics. For short pulse lasers.

30. Glass and Glass-ceramic

30.1 Glass-ceramics

- Cast like glass, then controlled crystallization $\rightarrow$ very low thermal expansion and high thermal-shock resistance
- Applications: cooking hobs, precision mirror materials

30.2 Glass basics

Network concept: network formers (SiO_2, B_2O_3) + modifiers (Na_2O, K_2O) that reduce viscosity and the glass transition temperature.
Glasses have amorphous structure (transparents).

30.2.1 Float glass surface

- Lower surface: contacts liquid tin bath $\rightarrow$ very smooth
- Upper surface: flame-polished in the float proces $\rightarrow$ very smooth

30.2.2 Production of glass

- Hollow glass: glass blowing
- Flat glass: float glass process, drawing, pressing

30.3 Main glass types

30.3.1 Quartz glass

- High melting point, high viscosity, high temperature resistance, low thermal expansion, chemical resistance
- Applications: laser optics, lamps, fireproof stove windows

30.4 Other glasses

30.4.1 Soda-lime glass

Cheap, easy to form, limited thermal-shock resistance. Used for windows and bottles.

30.4.2 Borosilicate glass

Low thermal expansion gives high thermal-shock and chemical resistance. Used for labware and cookware.

30.4.3 Lead oxide containing glass

High refractive index and density (good optics/radiation shielding) but heavier and more toxic/regulated.

30.5 Glass strengthening

30.5.1 Thermal toughening

Rapid cooling creates compressive surface stresses.

30.5.2 Chemical toughening

Ion exchange ($Na^+ \to K^+$) creates compressive surface layer (display glasses). As a result, compressive stress increases

IX. Polymers, Recycling, and FRP