Material Science – Schillfahrt

Overview
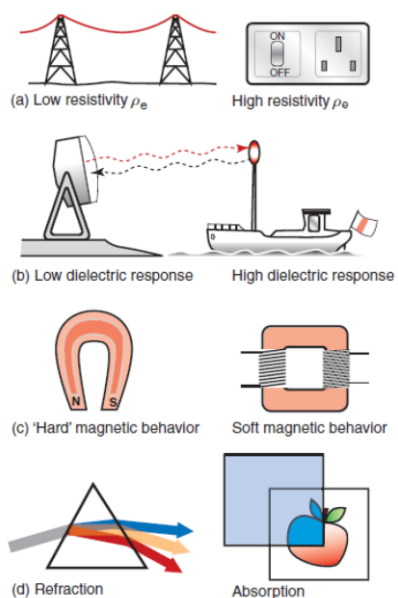
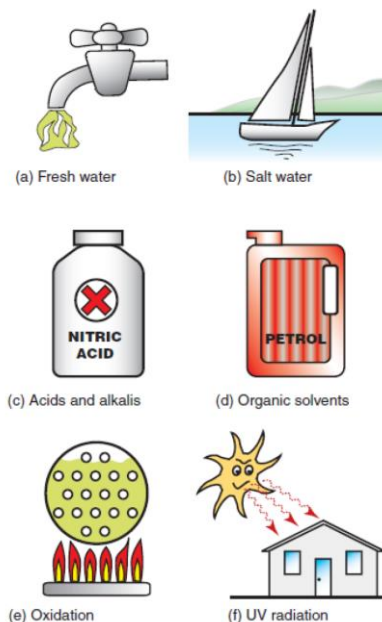**mechanical**

(a) All as it should be

(b) Not stiff enough (E too low)

(c) Not strong enough (σ_y too low)

(d) Not tough enough (K_{1c} too low)

(e) Too dense (ρ too high)

thermal

(a) High service temperature T_{max} Low service temperature T_{max}

(b) High expansion coefficient α Low expansion coefficient α

(c) High conductivity λ Low conductivity λ

(d) High T-diffusivity a Low T-diffusivity a

electrical

(a) Low resistivity ρ_e High resistivity ρ_e

(b) Low dielectric response   High dielectric response

(c) 'Hard' magnetic behavior   Soft magnetic behavior

(d) Refraction   Absorption

chemical

(a) Fresh water   (b) Salt water

(c) Acids and alkalis   (d) Organic solvents

(e) Oxidation   (f) UV radiation

Class	Property	Symbol	Unit
General	Density	ρ	(kg/m³)
	Price	C_m	($/kg)
Mechanical	Elastic Moduli (Young´s, shear, bulk)	E, G, K	(GPa)
	Yield strength	σ_y	(MPa)
	Tensile (ultimate) strength	σ_{ts}	(MPa)
	Failure strength	σ_f	(MPa)
	Compressive strength	σ_c	(MPa)
	Elongation at ruptur	ε_f	(-)
	Elongation at yield	ε_y	(-)
	Poisson´s ratio	ν	(-)
	Hardness (Vickers, Brinell, Rockwell B, Rockwell C)	HV, HB, HRB, HRC	(HV, HB, HRB HRC)
	Fatigue endurance limit	σ_e	(MPa)
	Fracture toughness	K_{1C}	(MPa*m$^{1/2}$)
	Damping capacity (loss coefficient)	η	(-)
	Wear rate (Archard) constant	K_A	(MPa^{-1})

| Class	Property	Symbol	Unit
Thermal	Melting point	T_m	(°C or K)
	Glass temperature	T_g	(°C or K)
	Maximum service temperature	T_{max}	(°C or K)
	Maximum service temperature	T_{min}	(°C or K)
	Thermal conductivity	λ	(W/(m*K))
	Specific heat	C_p	(J/(kg*K))
	Thermal expansion coefficient	α	(K^{-1})
	Thermal shock resistance	ΔT_s	(°C or K)
Electrical	Electrical resistivity	ρ_e	(Ω*m or $\mu\Omega$*cm)
	Relative permittivity	ε_r	(-)
	Breakdown potential gradient	V_b	(10^6 V/m)
	Dielectric loss factor	P	(-)
Optical	Refractive index	n	(-)
Ecological	Embodied energy	H_m	(MJ/kg)
	Carbon footprint	CO_2	(kg/kg)

Elastic Modulus
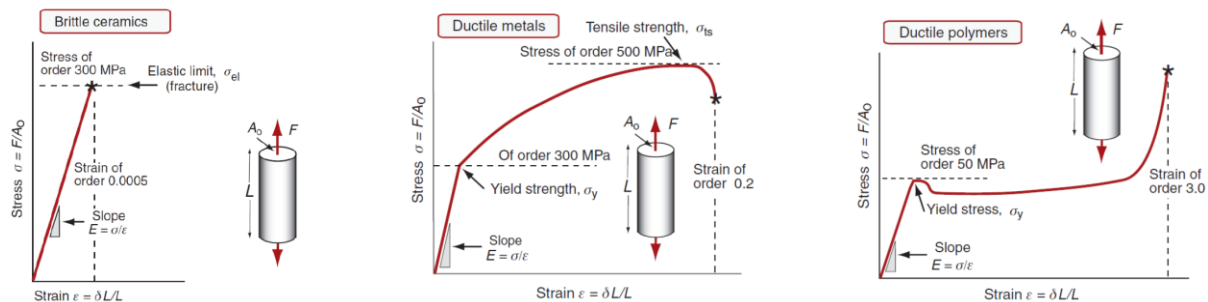
Difference between isotropic and anisotropic materials!

Poisson´s Ratio

exotic

Range: $-1 \dots 0.5$

most material ~ 0.3

$$\nu = -\frac{\varepsilon_{yy}}{\varepsilon_{xx}}$$

$$\varepsilon_{xx} = \frac{L_1 - L_0}{L_0} = \frac{\Delta L}{L_0}$$

$$\varepsilon_{yy} = \frac{d_1 - d_0}{d_0} = \frac{\Delta d}{d_0}$$

Stress Strain curve
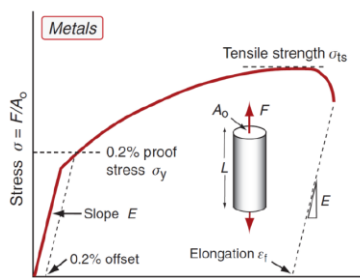
Tensile strength: stress, where instability begins (σ_{ts})

Yield strength: stress, where plastic deformation begins (σ_y)

Elastic limit: stress, where elasticity ends (σ_{el})

Tensile strain at break: elongation, after fracture (ε_f)
It is a parameter of the ductility.

If we think about the **energy stored** in a system:

$$dW = F \cdot dL$$

And we define this as energy per unit volume

$$dW = \frac{F \cdot dL}{A \cdot L_0} = \sigma \cdot d\varepsilon$$

- crash box

Hardness

Vickers, Brinell, Rockwell, Shore, Knoop

Pressing different shapes with a defined force into a specimen.

Fracture Toughness

Ability to withstand a certain stress at crack zones

K_{1C}

Fatigue behaviour
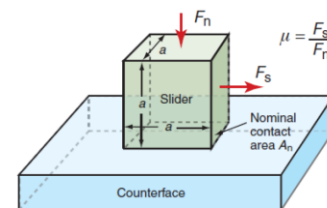
Wöhler Curve
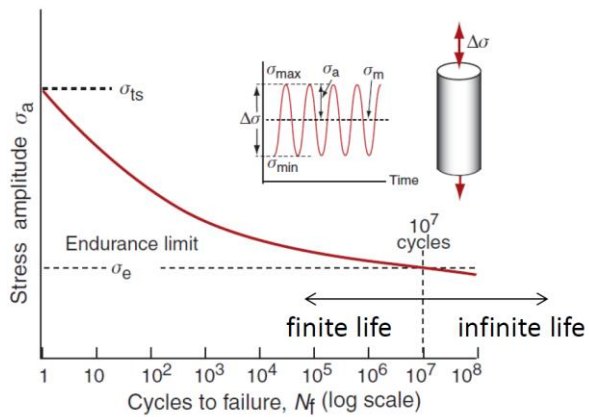
Damping capacity

Measure of internal friction, measures the degree to which a material dissipates vibrational energy

Wear rate

$$W = \frac{Volume\ of\ material\ removed\ from\ contact\ surface\ (m^3)}{Distance\ slid\ (m)}$$

$$W = k_A \cdot P \cdot A_n$$
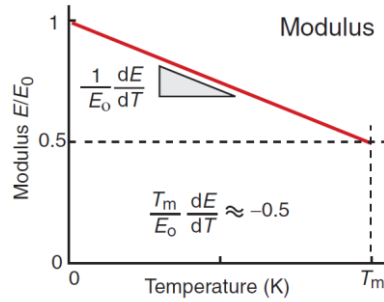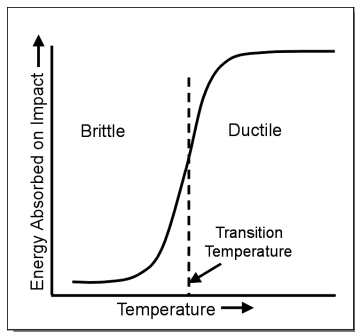
P... pressure (MPa)
A_n ... nominal contact area

Creep deformation

A typical creep curve, which is measured by a creep tests (*constant loading, constant temperature*) is the same for metals, ceramics and polymers

Melting point and glass transition temperature

Maximum service temperature

More thermal properties

- Thermal conductivity λ (W/mK)

- Specific heat c_p (J/kgK)

- Thermal diffusivity a (m²/s) $a = \dfrac{\lambda}{\rho\, C_p}$

- Thermal expansion coefficient α (1/K) $\varepsilon_T = \alpha\,\Delta T$

- Thermal shock resistance ΔT_s
  maximum temperature difference through which $\Delta T_s = \dfrac{\sigma_{TS}(1-\nu)}{E_{TS}\alpha_T}$
  a material can be quenched suddenly without damage

Electrical properties

- Electrical resistivity (ρ_e in Ωm) or electrical conductivity (reciprocal value, S/m)
- Relative permittivity (dielectric constant) (ε_r in -)
- Breakdown potential (V_b 10^6 V/m)
- Dielectric loss factor (L in -)

    …measures the energy dissipated by a material (as heat) in an oscillating field [2]

Refraction index

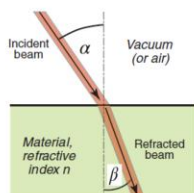$$n = \frac{c}{v} = \frac{\sin \alpha}{\sin \beta}$$ c … speed of light in vacuum
     v … speed of light in the material

$$\boldsymbol{n} \approx \sqrt{\varepsilon_r}$$ … for nonmagnetic materials

$$R = \left(\frac{n-1}{n+1}\right)^2 \times 100$$ … percentage of reflected light

Eco properties

Embodied energy and undesired gas emissions (e.g. CO2 footprint ~equivalent)
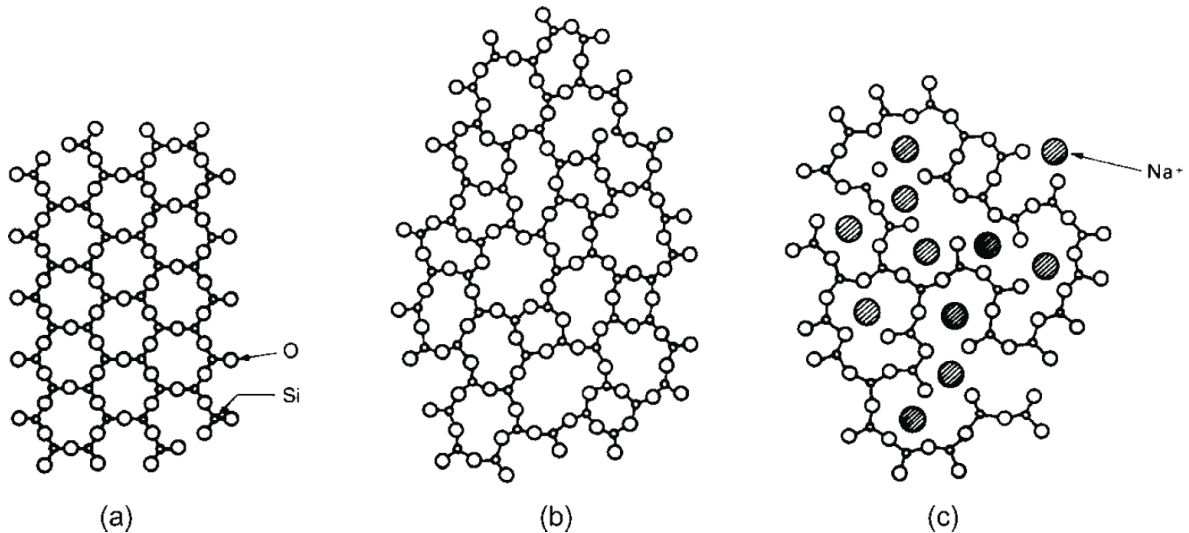
In which life cycle phase???

Ceramics

…are **inorganic**, **non-metallic** solids. Either **crystalline**, **amorphous** or **semi crystalline**

…formed by the application of heat (sometimes pressure)

…at least two elements, one of them non-metal or non-metallic solid

…strong ionic or covalent bondings

Structures

a) Crystalline structure   Quartz

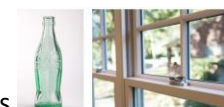b) amorphous structure   Quartz glass, fused quartz
        has no specific melting point – glas temperature point

c) amorphous structure with network modifier   glass for bottles, windows

        network modifier reduces manufacturing temperature

Five classes of ceramics (Ashby)

1. Glasses (based on silica SiO_2)
2. Vitreous ceramics (traditional clay products)
3. High-performance ceramics (high wear resistance and temperature capability)
4. Cement and concrete (essential for civil engineering)
5. Rocks and minerals

Classification of technical ceramics:

1. Silicate ceramics (all based on SiO_2)
2. Oxide ceramics (Aluminium & Magnesium Oxides)
3. Non-Oxide ceramics (carbide & nitride)

Microstructures of ceramics

Issues according to the manufacturing process – drawing with direction & heat elongation
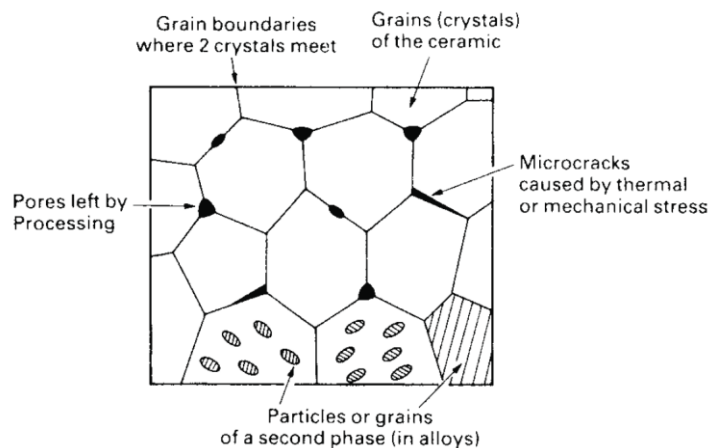
Advantages for technical ceramics

- High hardness
- Excellent wear resistance
- High temperature stability

Disadvantages for technical ceramics

- Brittle material behaviour
- Low value of elongation at rupture
- Difficult to fabricate

Ceramics are often used at high maximum service temperatures
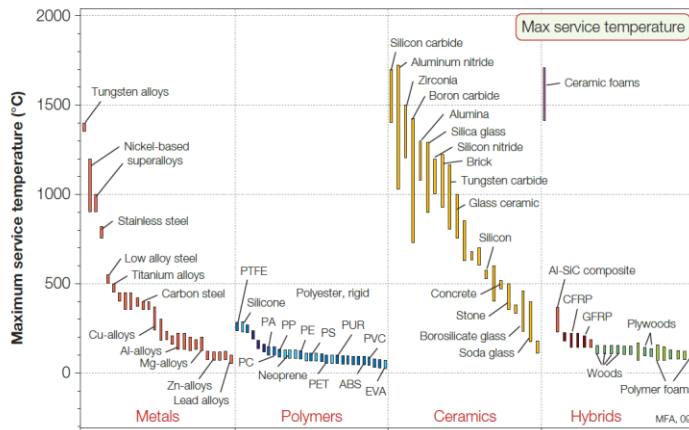
For coatings the thermal expansion has to be similar to the base material – otherwise cracks/damage
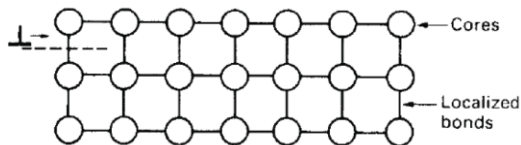
Piezoelectric effect

- Direct effect – voltage via compressive stress
- Inverse effect – small movement via voltage

Applications: force sensor, ultrasonic actuators, electrical elements (medical ultrasonic device)
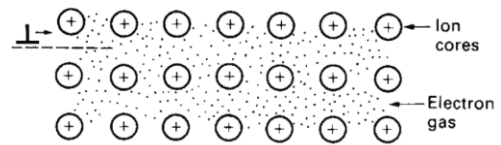
Hardness

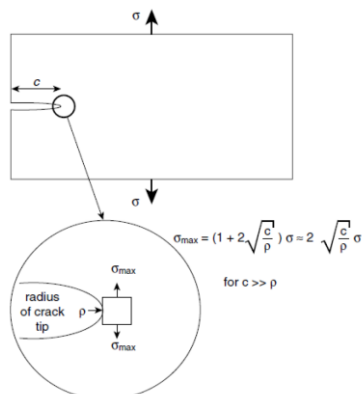Hardest of solids without further treatments (like metals) – because of covalent bondings

Very poor fracture toughness

brittleness

$$\sigma_{max} = (1 + 2\sqrt{\frac{c}{\rho}})\,\sigma \approx 2\sqrt{\frac{c}{\rho}}\,\sigma$$

for $c \gg \rho$
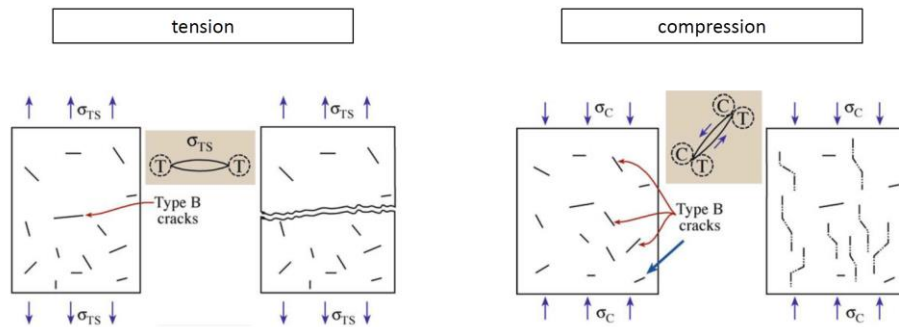
$$\sigma_{TS} \approx \frac{K_c}{\sqrt{\pi a_m}}$$

K_c ...(MPa m$^{1/2}$)

a_m =c (for surface cracks)

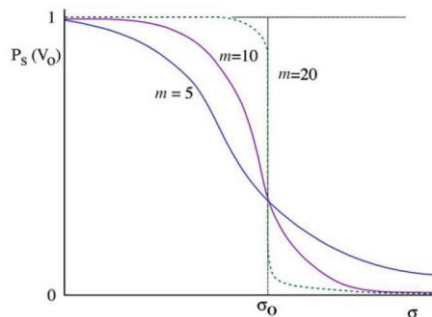a_m =c/2 (for internal cracks)

Crack propagation

Cracks open under tension and close under compression

Weakest link fracture theory

Weakest link gives up first – therefore just fibre (glass fibre, carbon fibre)

CF   ø7µm

GF   ø15µm

Human hair   ø50µm

Weibull distortion

The higher the Weibull modulus, the lower is the variability of strength
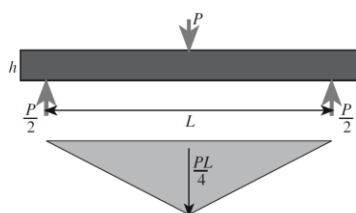
e.g ceramics m=5-20; steel m=~100

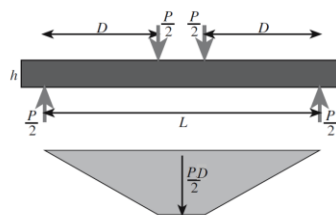compared to the max tensile strength (no yield strength!)

Tests

Just bending – clamping could damage

Four-point bending – weakest link theory...

Ceramics – design guidelines

Most important – avoid stress concentration

- Leaps (jumps) of the cross-section should be avoided
- Sharp edges should be avoided
- Preferably compressive load
- High edge loading should be avoided
- Differences of the coefficient of thermal expansion must be considered (ceramic coatings...)

- ceramics tend to creep at high temperatures (>1/3 T_M)
- Ceramics sometimes show a timed dependency of strength: slow crack growth
- Thermal shock resistance has to be considered (temperature differences)

Sintering

Process with high temperatures and pressure ($T>0,5*T_M$)

- Fine particles sinter much faster than coarse ones because the surface area (and thus the driving force) is higher and the diffusion distance are smaller.
- The rate of sintering varies with temperature in exactly the same way as the diffusion coefficient. Higher temperatures accelerate the sintering process.

Sintering by applying pressure and temperature (hot pressing or hot isostatic pressing HPing)

(a)   (b)   (c)
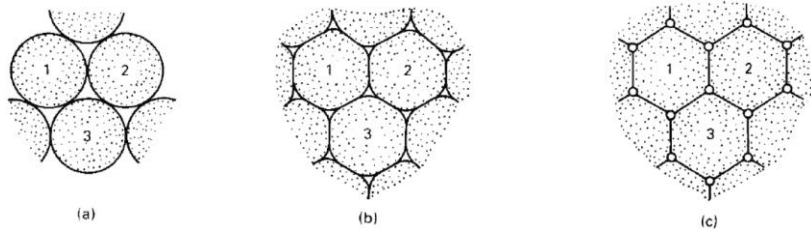
Polymers

Types of polymers:

- Standard plastics
- Technical design plastics
- High temperature plastics

Key to mass production... (most of the parts in the automotive sector)

Structure:

Macromolecules with strong covalent bonds

Long chains – like spaghetti

Thermomechanical properties defined by secondary binding forces (intermolecular bonds)
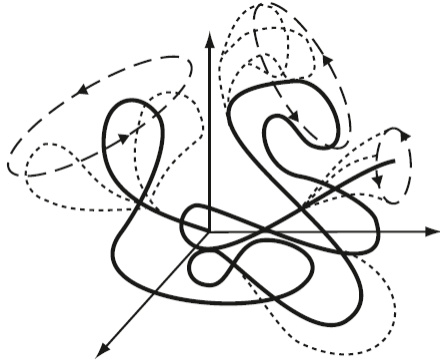
Dispersion forces lead to crystalline structures

Hydrogen bonds:

...are very strong bondings – PA6 has often those bondings -> reason for high usage
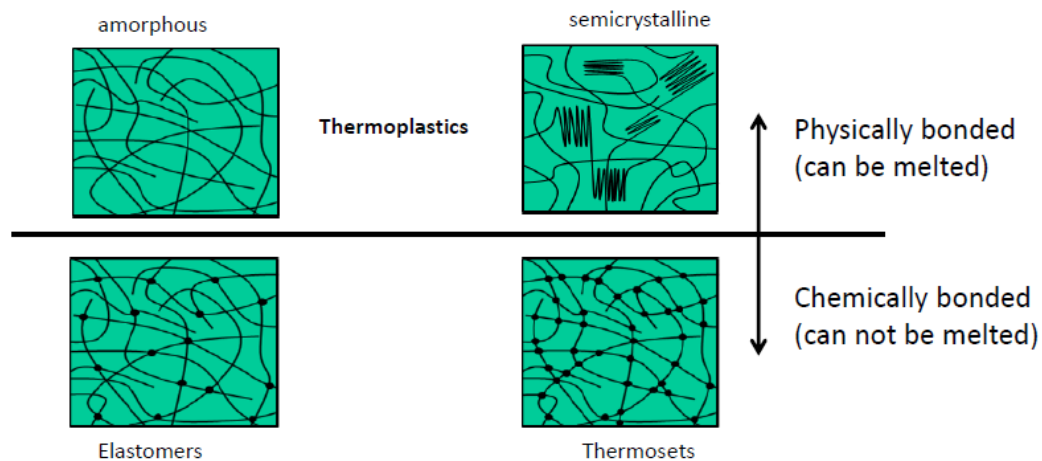
Steric hindering:

Flexibility because bonds have ability to rotate

Want to get at energy minimum -> reason for deformation...

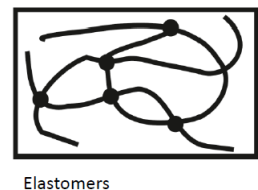Semi crystalline polymers – get in regular older

Classes of Plastics:

Elastomers:

...almost linear polymers – occasional cross -links (2nd bonds already melted at room temperature)

Elastomer	Examples / Applications
Polyisoprene	Natural rubber
Polybutadiene	Synthetic rubber, car tires
Polychloroprene	Neoprene: An oil-resistant rubber used for seals

Elastomers

Thermosets:

...are made by mixing two components which react and harden (1 resin & 1 hardener) – heavy cross-linked – cant be hot-worked

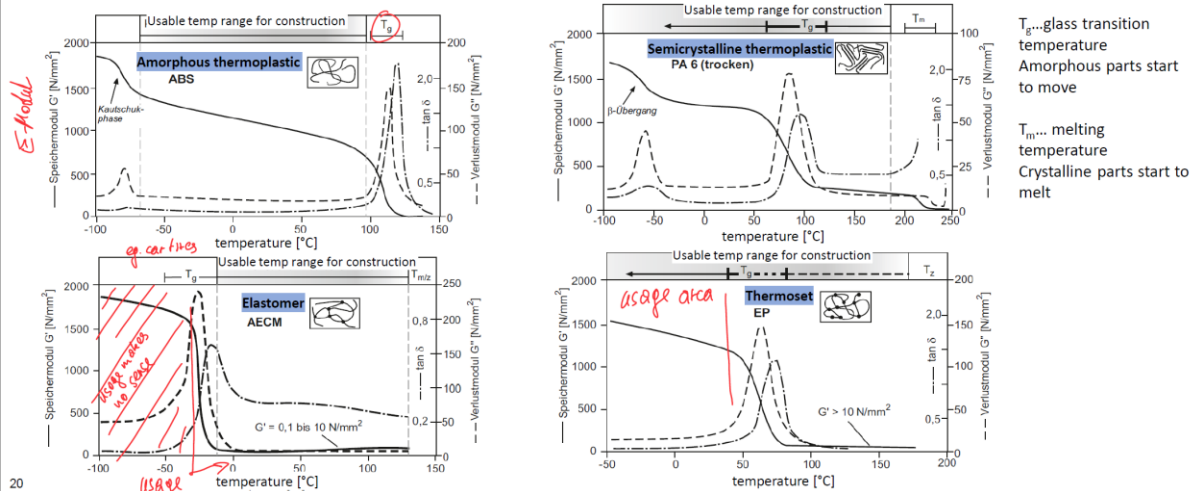| Thermoset	Examples / Applications
Epoxy	Fiberglass, adhesives. Expensive.
Polyester	Fiberglass, laminates. Cheaper than epoxy.
Phenolformaldehyde	Bakelite, Tufnol, Formica. Rather brittle.
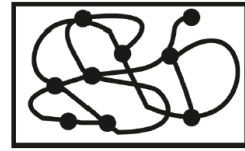
Thermosets

4 Groups (important slide!)

Explanation:

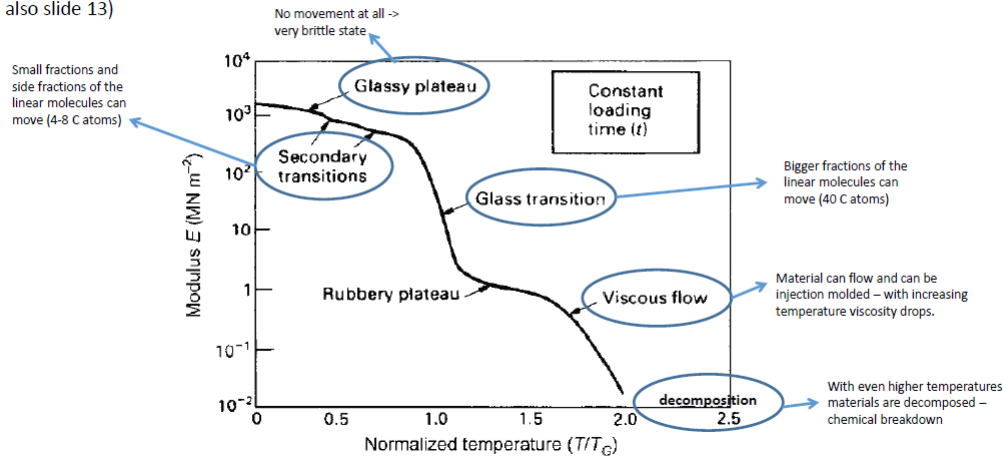Amorphous thermoplastics - no melting - decomposition

Semicrystalline thermoplastics – glass transition point and melting point due to cystanline structure which gets "solved"

Elastomers – no melting point due to strong cross-link bondings – just decomposing

Thermosets – no melting point due to strong cross-link bondings – just decomposing

Discussion of the E-Module according to the temperature

What's happening on the molecular basis at those transition points for an amorphous thermoplastic (see also slide 13)
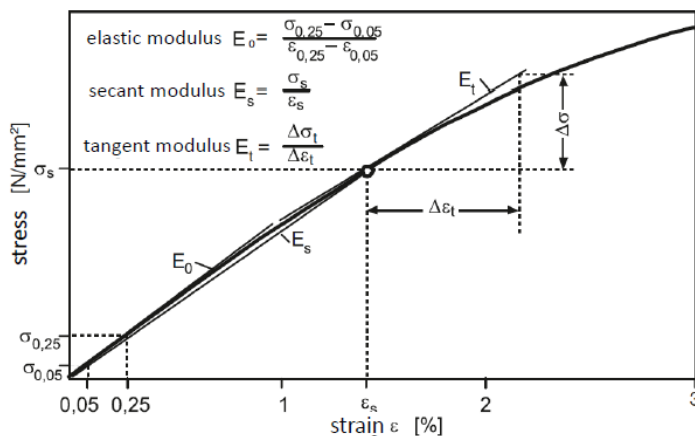

No movement at all -> very brittle state

Small fractions and side fractions of the linear molecules can move (4-8 C atoms)

Bigger fractions of the linear molecules can move (40 C atoms)

Material can flow and can be injection molded – with increasing temperature viscosity drops.

With even higher temperatures materials are decomposed – chemical breakdown

Polymers are not only dependent on **temperature** but also **time** dependent

Because of their long chains (molecules) – change over time

Thermomechanical properties

Mosty secant modulus

elastic modulus $E_0 = \dfrac{\sigma_{0,25} - \sigma_{0,05}}{\varepsilon_{0,25} - \varepsilon_{0,05}}$

secant modulus $E_s = \dfrac{\sigma_s}{\varepsilon_s}$

tangent modulus $E_t = \dfrac{\Delta\sigma_t}{\Delta\varepsilon_t}$

The elastic modulus E_0 is determined between 0,05 % and 0,25 % strain and is mainly used for material selection.

The secant modulus E_s is determined as a secant with a specific stress σ_s and strain ε_s, e.g. at 1 % strain (very often in secant modulus-strain diagrams)

POM: CELCON CF802 (look at campusplastics.com)
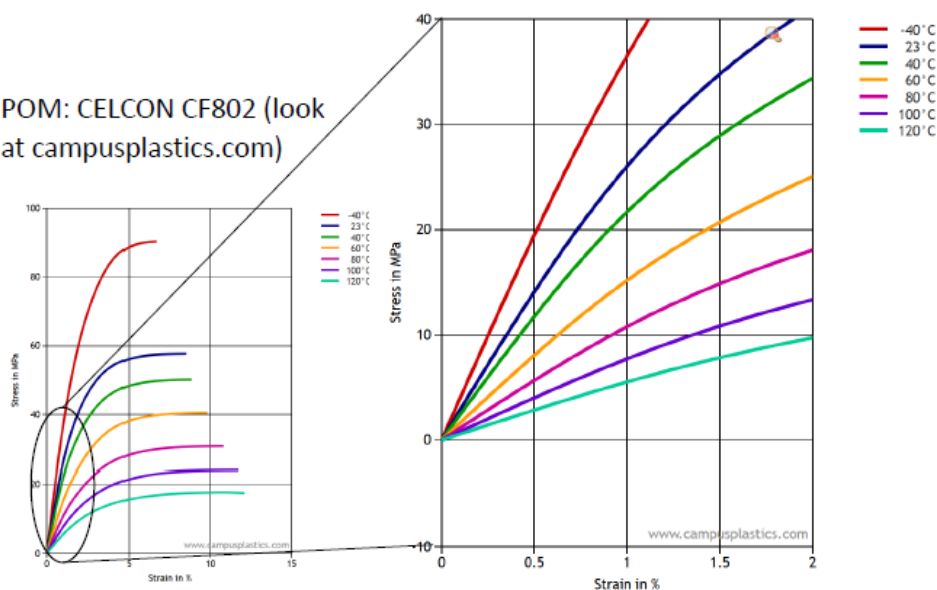
Creeping of polymers

Polymers tend to creep (some even at room temperature)

Parts of deformation:

- Elastic part (back to original shape)
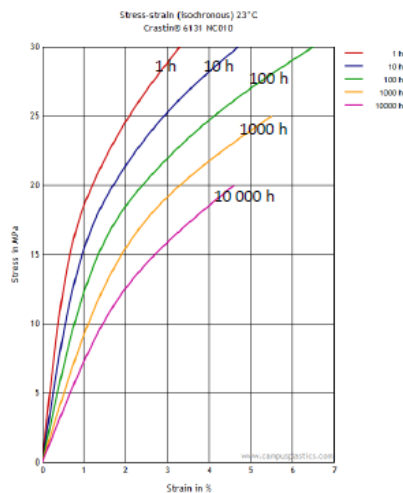
$$\varepsilon_0 = \frac{\sigma_0}{E_0}$$

- Viscoelastic part (after a certain time period back to original shape)

$$\varepsilon_{rel} = \frac{1}{E_{rel}}\left(1 - e^{-t/\tau}\right) \cdot \sigma_0 \quad mit \quad \tau = \eta_{rel} / E_{rel}$$
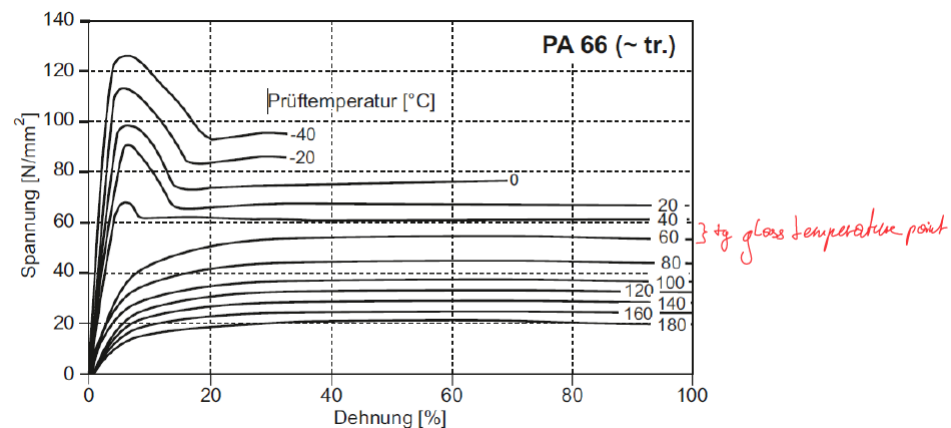
- Viscous part (permanent deformation)

$$\varepsilon_v = \frac{t \cdot \sigma_0}{\eta_0}$$
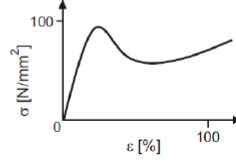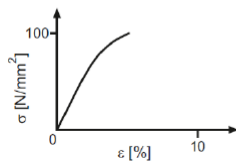
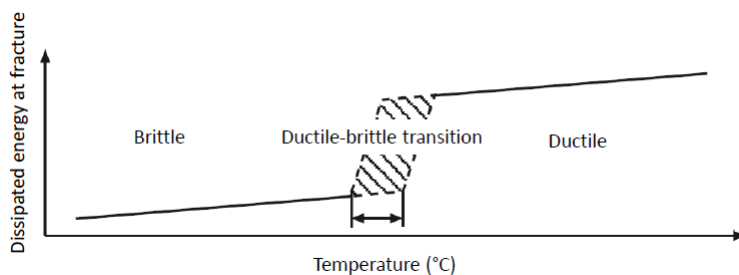- Isochronous stress-strain diagram for polymers

Thermomechanical behaviour:

Time dependency at fracture:

high	loading velocity	low
low	temperature	high
brittle	fracture	ductile

Some materials are stronger when loads are fast applied.

Fracture toughness:

Stiffness, max Yield-Strength and Fracture Toughness -> depend on temperature

- **T_{min} and T_{max} of a system have to be known!**

Water absorption

...can make polymers more ductile (especially with polar side groups e.g. PA6)

Types of fracture:

- Brittle fracture   no movement of polymer chains possible
  below 0,75 T_G -> low toughless materials – avoid stress concentration
- Cold drawing (Kaltziehen)   mainly in partially crystalline polymers
  Normally not considered – phase after yield to fracture
- Crazing (Rissbildung)   in polymers with higher T_G -> amorphous polymers
  No reduction in the cross-sectional area -> increase in volume
- Shear banding (Scherbildung)   can also occur in tension (mixture with crazing)

Design Guidelines for Polymers

- Flexible structures
  - Low modulus (elastomers)
  - Flexible structural design (thin walled)
  - Direction of force (torsion or bending)
- Stiff structures
  - Design is more important than the material stiffness

    $$\frac{h_{Mat1}}{h_{Mat2}} = \sqrt[3]{\frac{E_{Mat2}}{E_{Mat1}}}$$ e.g. aluminium: 70 000 N/mm²;   Determine the thickness ratio!
   PA6-GF40: 9 000 N/mm²

  - Always consider incorporation of ribs, stiffener beads or joining of two half-shells
  - Closed, hollow profiles show best stiffness to weight ratio

- Thermal expansion
  - Consideration of higher tolerances
  - Combination with stiffer materials (outsert technique)
- Construction of joints
  - Use of different materials which do not mix e.g. POM and PA

Hybrids

At least two combined material families
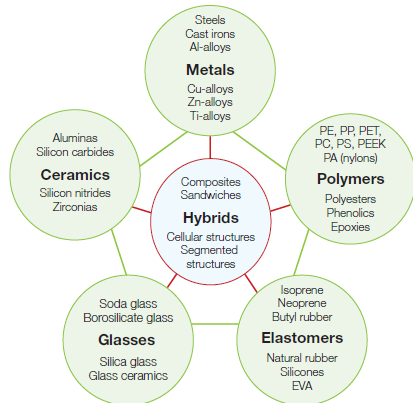
Reason: => improve/strengthen material properties and cancel out weaknesses of materials
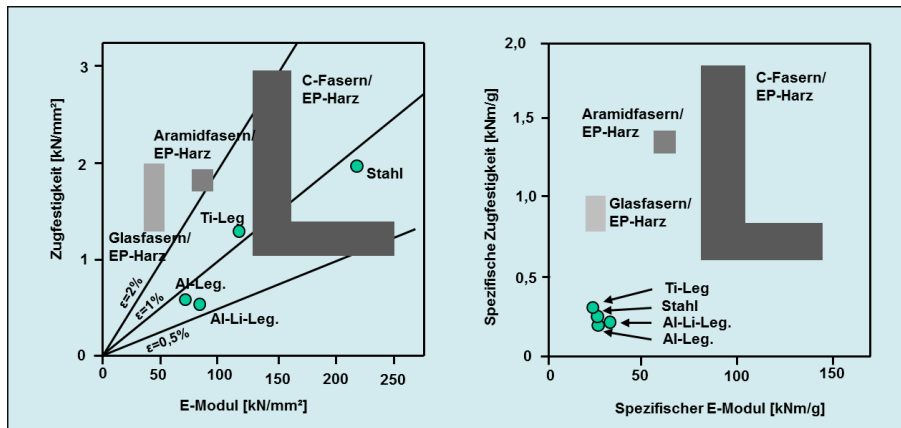
Properties:

- Strength
- Stiffness
- Impact
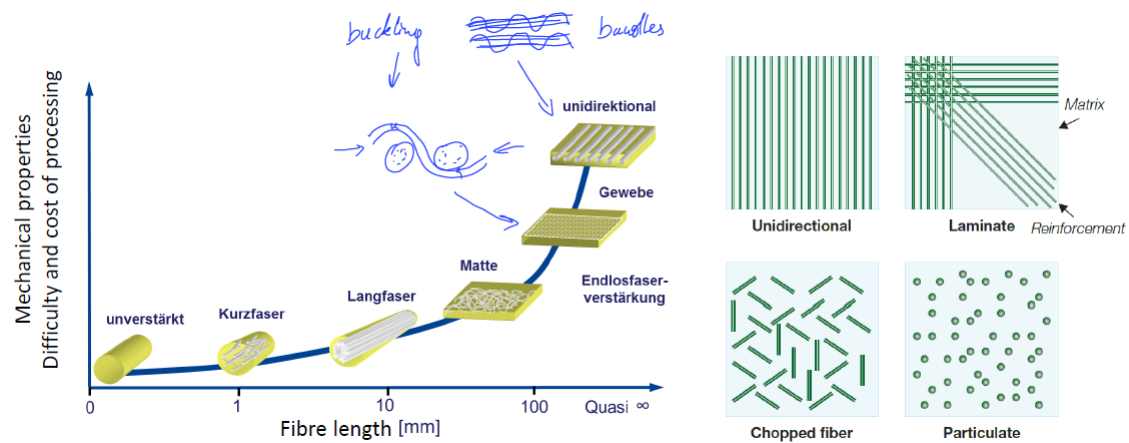- Density
- Thermal and electrical properties

Different approaches of mixture of properties:
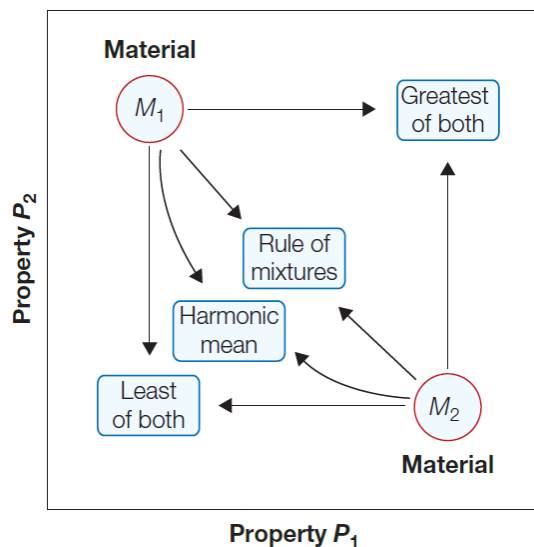
Reason why C-Fiber or G-Fiber Hybrids are often used in high performance sports:

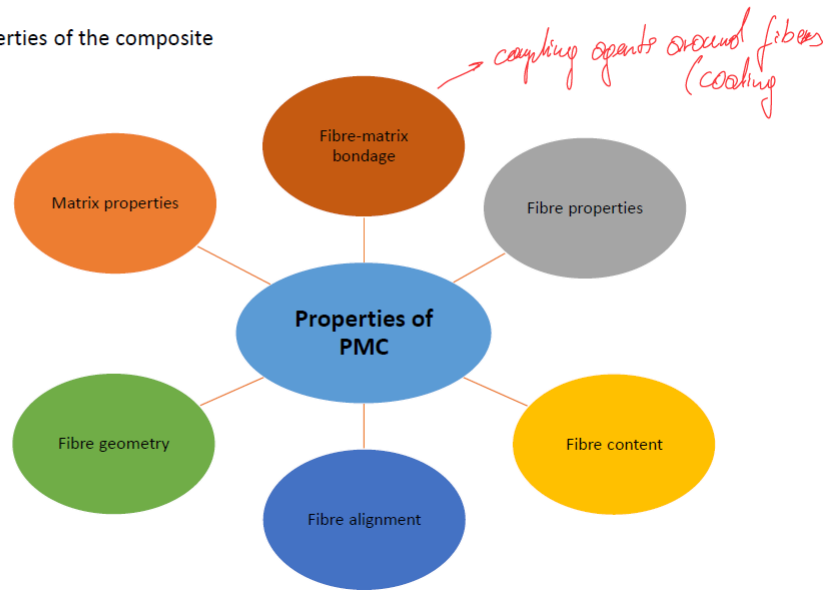Physical properties are highly dependent on the direction of the fibres:

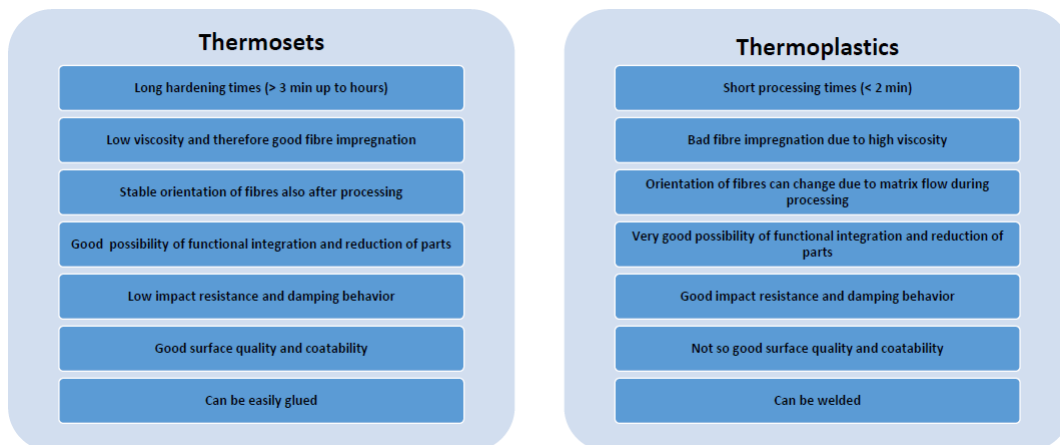Fibers have to be very thin -> weakest link theory ....

Composites – polymeric lightweight materials

What determines the properties of the composite

IMPORTANT EXAM

→ coupling agents around fibers (coating

Properties of PMC

- Fibre-matrix bondage
- Matrix properties
- Fibre properties
- Fibre geometry
- Fibre alignment
- Fibre content

Composites could be used with different matrix systems

Thermosets
- Long hardening times (> 3 min up to hours)
- Low viscosity and therefore good fibre impregnation
- Stable orientation of fibres also after processing
- Good possibility of functional integration and reduction of parts
- Low impact resistance and damping behavior
- Good surface quality and coatability
- Can be easily glued

Thermoplastics
- Short processing times (< 2 min)
- Bad fibre impregnation due to high viscosity
- Orientation of fibres can change due to matrix flow during processing
- Very good possibility of functional integration and reduction of parts
- Good impact resistance and damping behavior
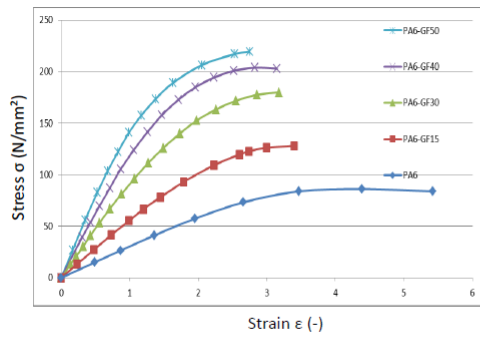- Not so good surface quality and coatability
- Can be welded

Main Fibre systems:

- Glass fibre
    - Cheap but heavy
- Carbon fibre
    - Light, very high elastic moduli and strengths, shows brittle failure
- Aramid fibre (Kevlar)
    - Light, good impact behaviour (damping), pure compression behaviour

Other Fibre systems:

- Polymer fibres (polyethylene, polypropylene)
- Natural fibres (flax, hemp, sisal)

Influence of the fibre content in the stress strain diagram

Stress σ (N/mm²) vs Strain ε (-)

PA6-GF50
PA6-GF40
PA6-GF30
PA6-GF15
PA6

because of injection molding

unidirektional
Glasfilamentgewebe
Rovinggewebe
Matte
Kurzfaser
unverstärkt

Fasergehalt (Gew %)
Zug-E-Modul (10² MPa)
Versagensspannung (MPa)