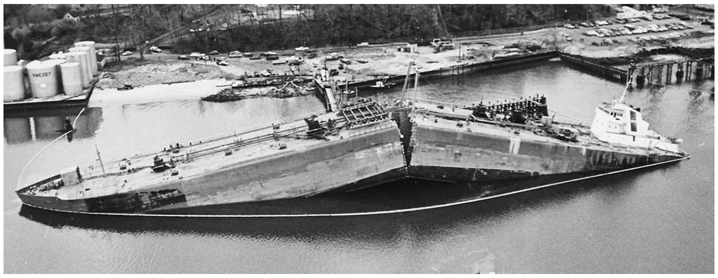
Failure, mechanical properties of ceramics and polymers

41680 Introduction to advanced materials



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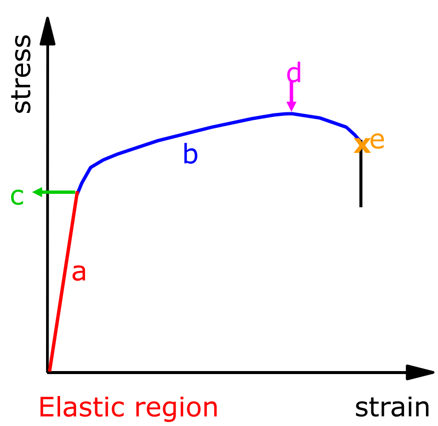
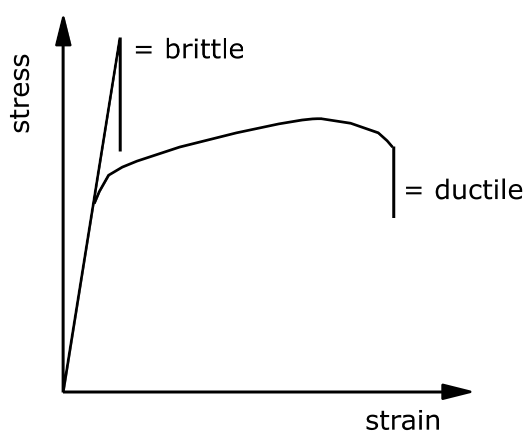
Stress strain curve



Elastic region
Plastic region
Yield strength
Tensile strength
Failure



Tensile properties

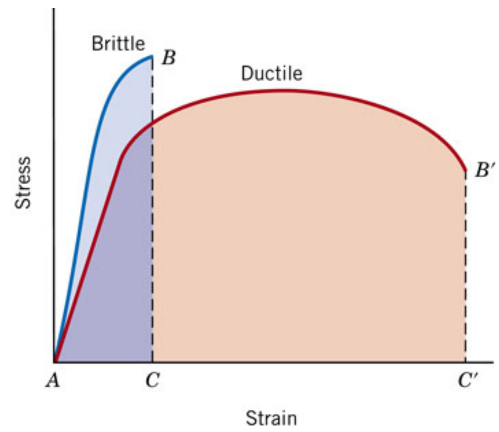
Ductility

=Strain to fracture ε_f

– ability for shape changes without fracture

– contrast: brittleness

- Strain to fracture ε_f
  - brittle $\varepsilon_f < 0.1$ %
  - ductile $\varepsilon_f > 10$ %
  - super-plastic $\varepsilon_f \approx 1000$ %
- Depends on
  - material and temperature !!!
  - crystal structure dependent (number of slip systems)



Unit of toughness and resilience

$1\ \frac{J}{m^3} = 1\ \frac{Nm}{m^3} = 1\ \frac{N}{m^2} = 1\ Pa$

Tensile properties (continued)

Toughness

=Area under stress-strain curve up to point of fracture

=Mechanical work until fracture

- Resistance to fracture
- Brittle materials are less tough

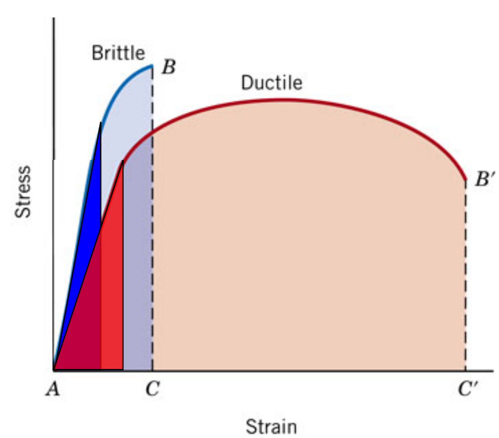
Resilience (modulus of resilience)

=Area under stress-strain curve before yielding

=Mechancial work until yielding

=Stored energy in elastic regime

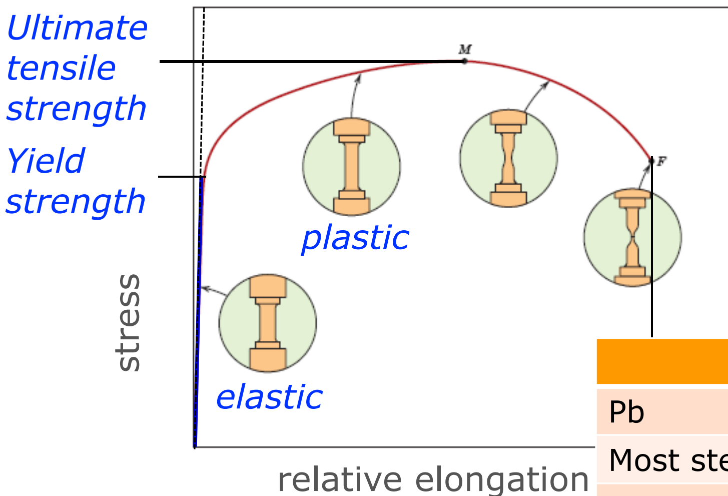
- Energy material can absorb without yielding $\frac{\sigma_y^2}{2E}$
- Ability to absorb energy and remain elastic (e.g. spring: high σ_y, low E)



Stress strain curve

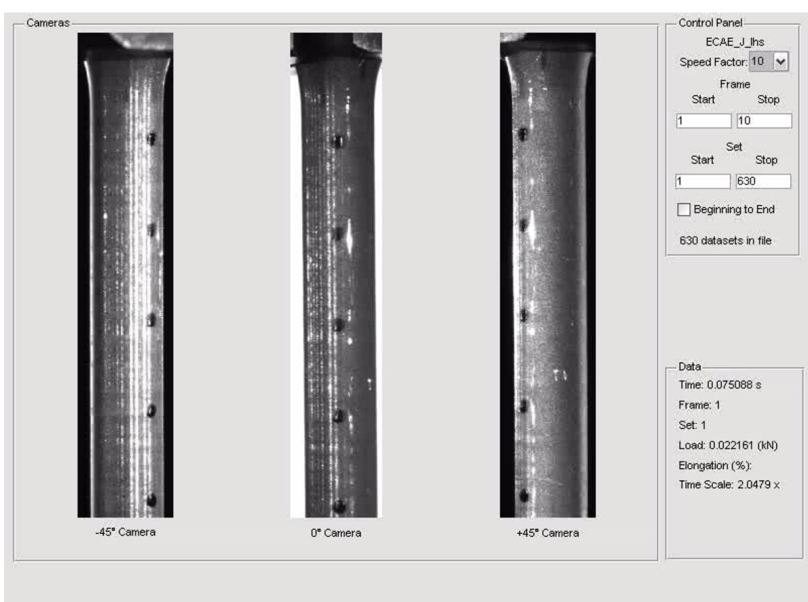
- yield stress σ_y
- resistance to plastic deformation

- ultimate tensile strength UTS
- marks the maximum achievable stress before failure (necking)

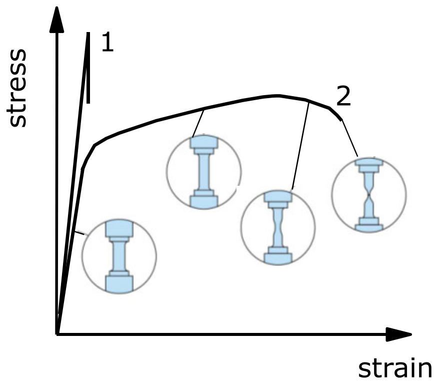


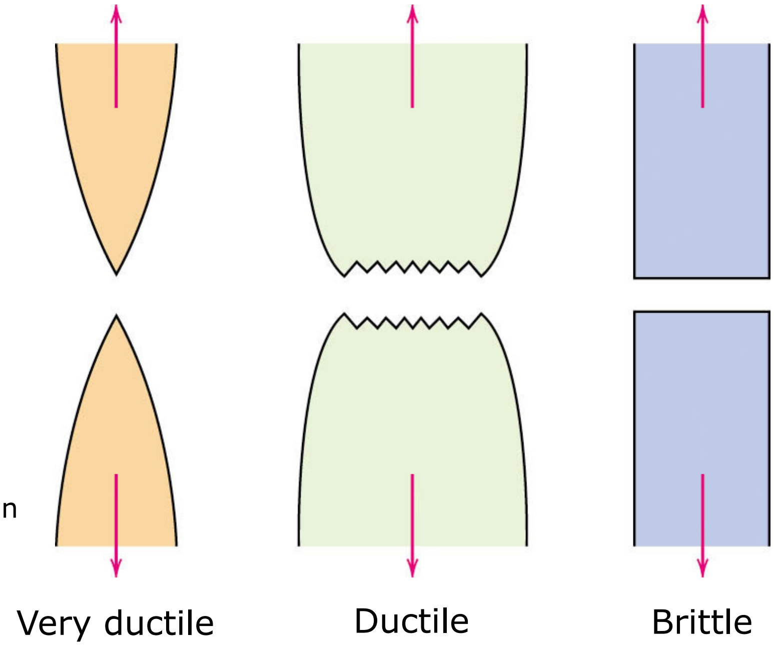
	UTS
Pb	10..20 MPa
Most steels	400..1200 MPa
Martensitic steels	2500..4500 MPa

Example of instrumented tensile test

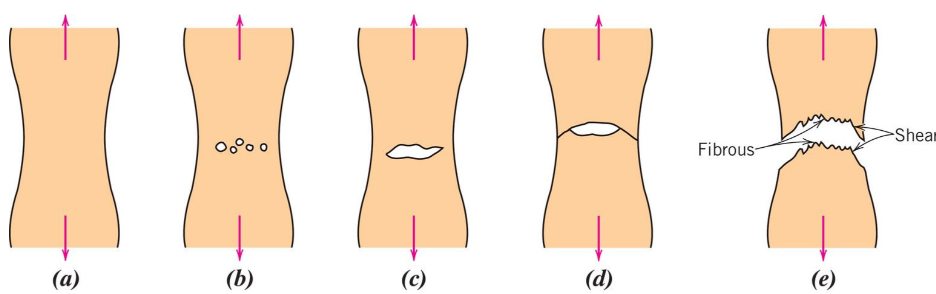


Failure





Ductile failure *(cup and cone)*



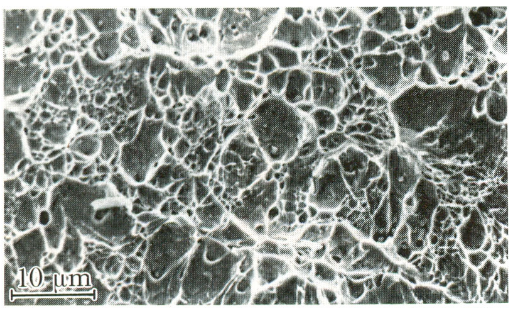
a) Necking
b) Small voids
c) Crack formation by coalescence of voids
d) Crack growth
e) Shear failure at the end

Cleavage surfaces

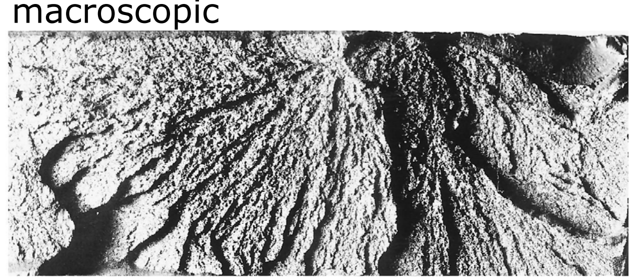
ductile

cup and cone

brittle

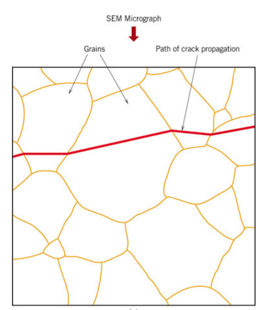


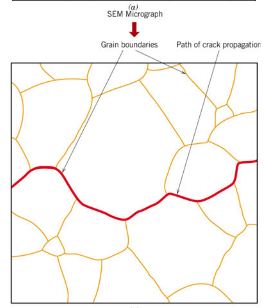
macroscopic



Cracks

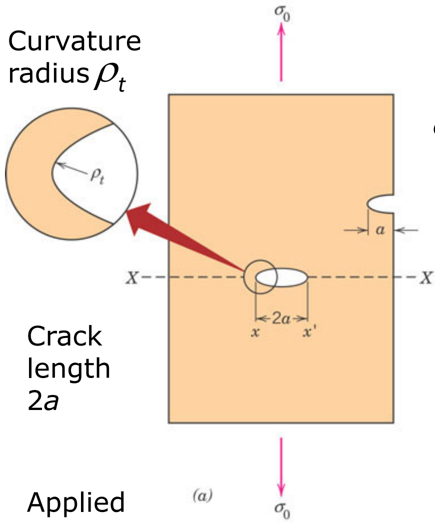
- Crack formation
  during manufacturing or during service
- Transcrystalline crack (= across grains)
  due to heterogeneous dislocation motion/activity
- Intercrystalline crack (= between grains)
  due to grain boundary sliding
- Cracks are not necessarily dangerous,
  only if the grow in an instable manner





Stress concentration at cracks

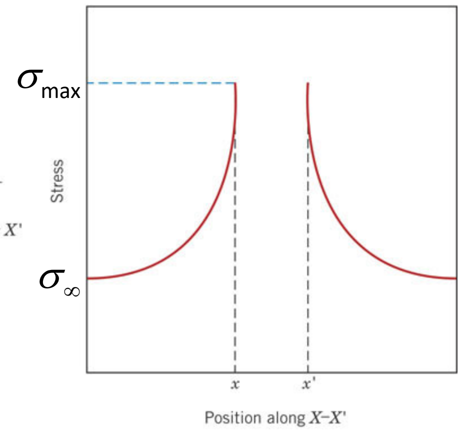
Curvature radius ρ_t



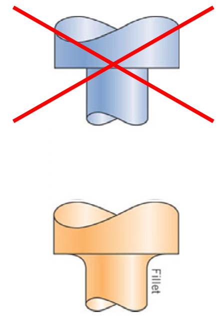
Crack length $2a$

Applied stress σ_0

Stress concentration



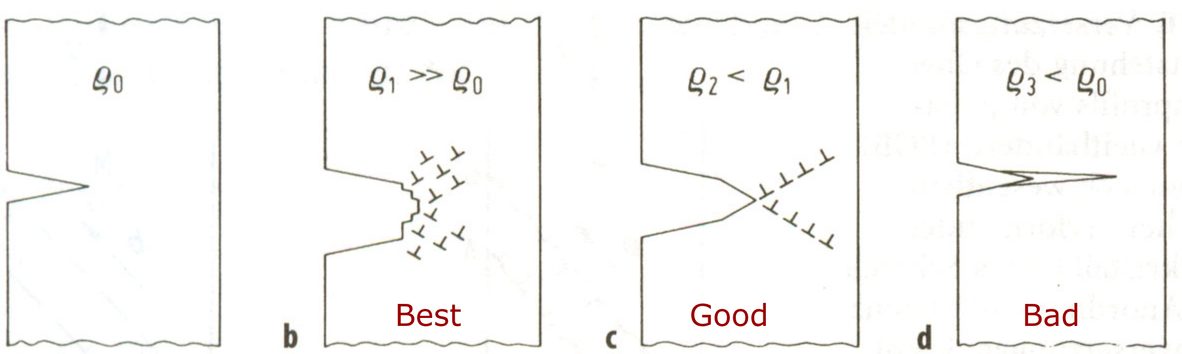
Design avoid edges



$$\sigma_{max} = \sigma_0\left(1 + 2\sqrt{\frac{a}{\rho_t}}\right) \approx 2\sigma_0\sqrt{\frac{a}{\rho_t}}$$

$$\sigma_{max} \approx 2\sigma_0\sqrt{\frac{a}{\rho_t}}$$

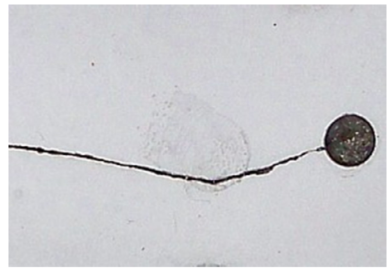
Crack growth



Crack with opening radius ρ_0 | Multiple slip | Localized slip | Without plastic deformation

- Plastic deformation ahead of crack tip
  - Blunts crack tip
  - Reduces stress concentration
  - Initially stable crack growth, before unstable crack growths starts
- Finally catastrophic crack growth and failure

Airplane fuselage



Fracture toughness

- Critical stress for crack growth in brittle material

$$\sigma_c = \sqrt{\frac{2E\gamma_s}{\pi a}}$$

Surface energy γ_s
Elastic modulus E
Crack length 2a

- New material parameter: fracture toughness K_{Ic}

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

  - Geometry factor $Y \approx 1$
  - for thick specimens
  - Y independent of crack length
  - K_{Ic} small for brittle material
  - K_{Ic} large for tough material

Fracture toughness

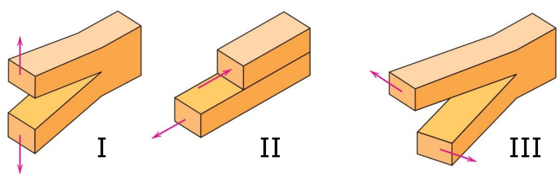
- Stress intensity factor

$$K_I = Y\sigma\sqrt{\pi a}$$

- Catastrophic crack growth
  (if stress intensity factor is larger than fracture toughness)

$$K_I = Y\sigma\sqrt{\pi a} \geq K_{Ic}$$

- Other loading modes



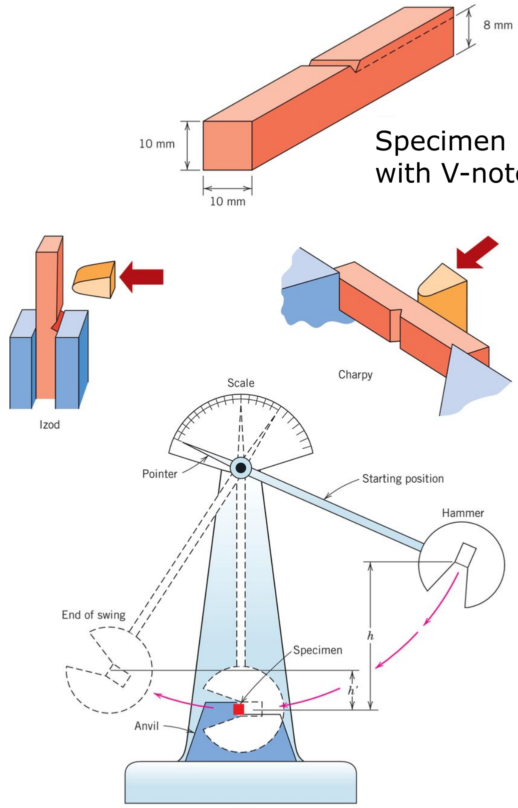
Ductile failure versus brittle failure

Constance Tipper, nee Elam

- Depends on
  - material: microstructure, crystal structure, chemical composition
  - conditions: atmosphere, temperature, load, ...
- Brittle failure occurs suddenly and fast
  speed of sound e.g. in steel 1000 m/s !!!
- Ductile to brittle transition temperature DBTT
  - Some metals (fcc: Al, Cu, Ni, stainless steel) remain ductile at low temperatures
  - bcc metals fail ductile at high T, but brittle at low T
  - hcp metals show different types of behavior

Toughness testing
Impact testing

- Ductile to brittle transition?
- Transition temperature

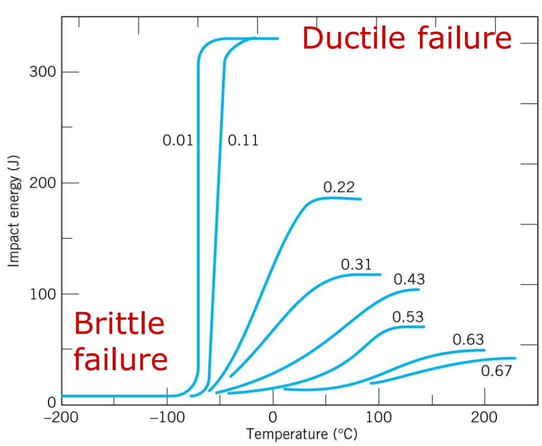


- Impact testing
- Measurement
  - Start height h
  - Swing height h'
- Energy loss

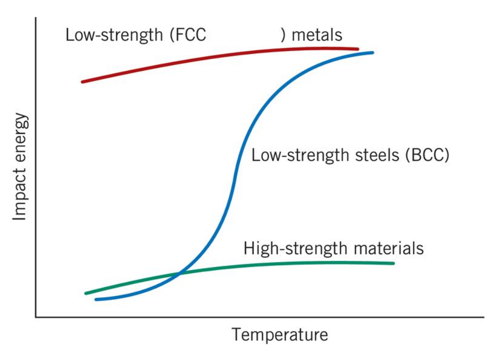
$$J = mg\left(h - h'\right)$$

Impact testing
Charpy impact test

- Example: steel with different carbon content



- General



- Hexagonal metals
  - with DBTT: Zn, Mg
  - without DBTT: Zr, Ti

Mechanical properties of ceramics

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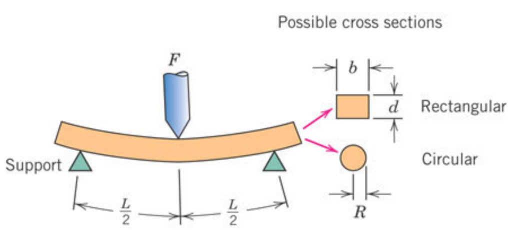
Mechanical testing of ceramics

- Three point bending test

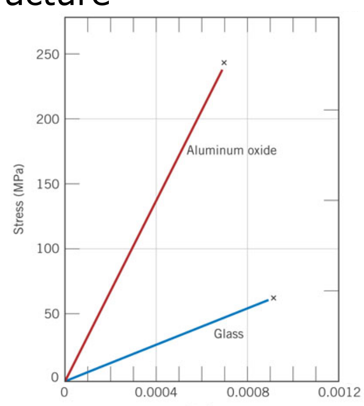


- Flexural strength

$$\sigma_{fs} = \frac{3FL}{2bd^2}$$

(rectangular cross section)

- Elastic behavior until fracture



- Yield strength = tensile strength

Mechanical properties of crystalline ceramics

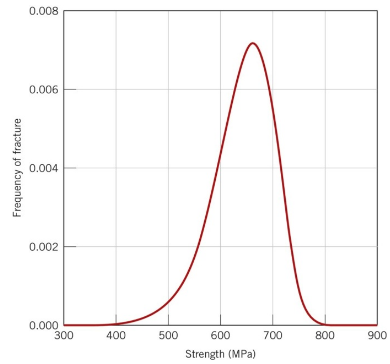
- Generally very brittle

Dislocations

- Motion may not to lead neighbors with same charge
- Low number of slip systems
- Limited deformability
- Low ductility
- Large specimen variation (Weibull distribution)

Micro cracks

- Also in amorphous ceramics
- Stress concentrations
- From manufacturing
- Can be removed on surface

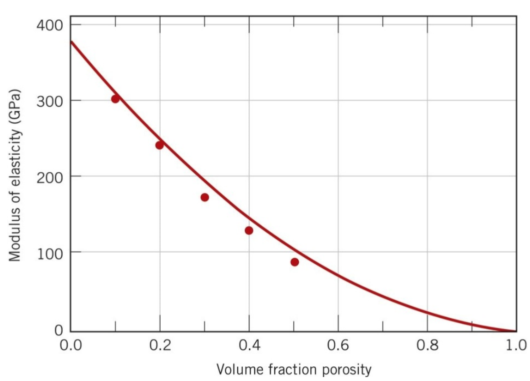


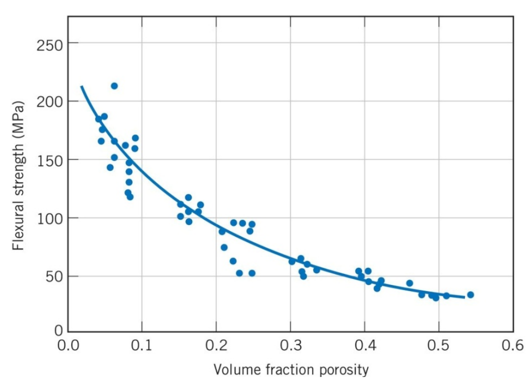
Effect of porosity

- Pores in material due powder sintering
- Porosity P (volume fraction of pores)

$$E = E_0\left(1 - 1.9P + 0.9P^2\right)$$

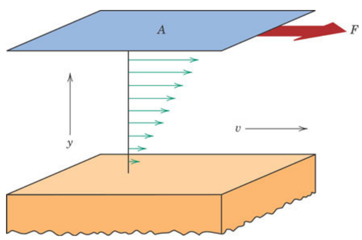
$$\sigma_{fs} = \sigma_{fs,0}\exp\left(-nP\right)$$





Mechanical properties of amorphous ceramics

- No crystalline lattice
- No dislocations
- Plastic deformation due to atomic jumps
- Shear test



- Viscous behavior

$$\tau = \eta \dot{\gamma}$$

- Comparable fluids
- Glass transition (empirical)

$$\eta_{cr} = 10^{12} \text{ Pa s}$$

Material	Viskosity
Water	$1{\cdot}10^{-3}$ Pa s
Olive oil	0.08 Pa s
Honey	2-10 Pa s

Mechanical properties of polymers

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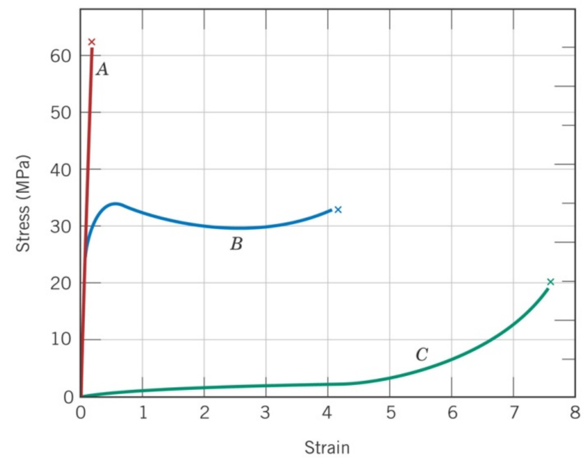
Mechanical properties of polymers

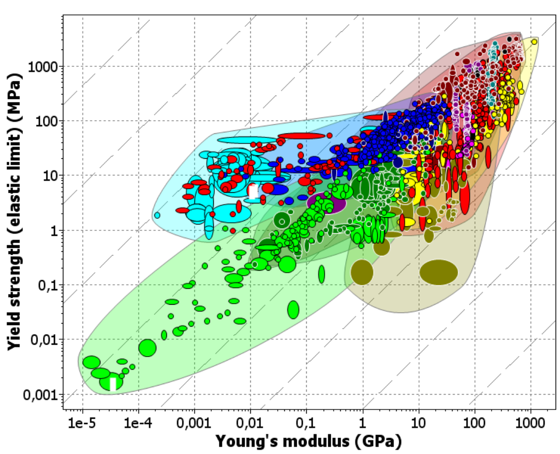
- Different types of behavior

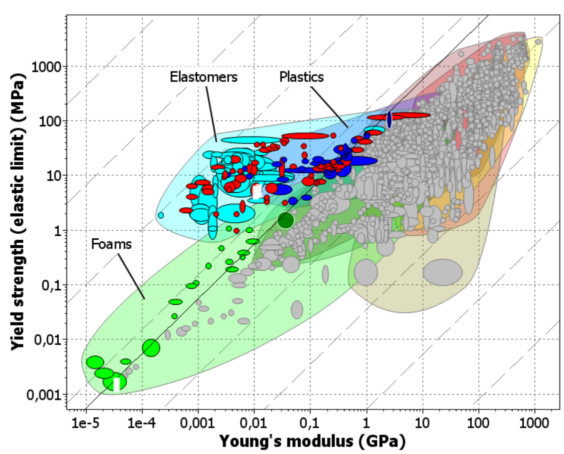
A. Brittle
B. Elastoplastic
C. Purely elastic (elastomers)



Property maps

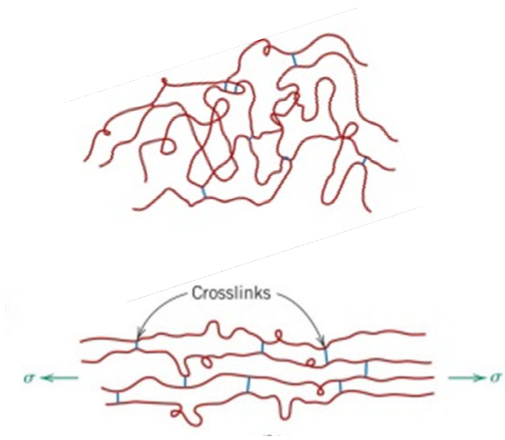
- Correlation between yield strength and *E*
- Theoretical yield strength (defect-free material) $\sigma_{th} = E/20$





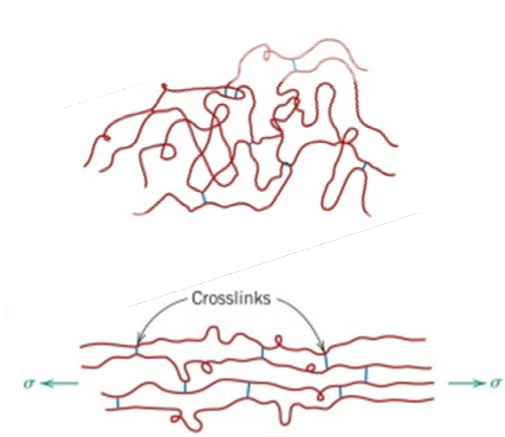
Elastomers	$\sigma > \sigma_{th}$	Chains, entropy
General	$\sigma \ll \sigma_{th}$	Defects

Elastomers
Elastic properties

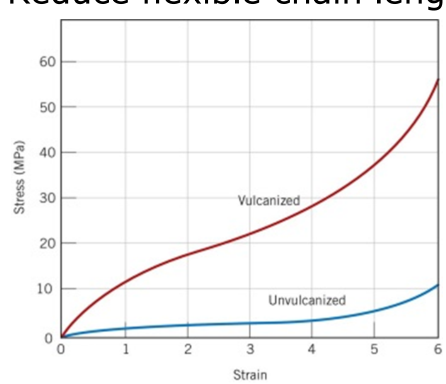


- Covalent cross bonds
- When load is removed
  - Curly conformation reestablished
  - Disorder increased (entropy!)
- Low modulus of elasticity
- Young’s modulus increases with increasing temperature
- Rubber becomes warm when stretched

Elastomers
Vulcanization



- Effect of cross bonds
- Reduce flexible chain length

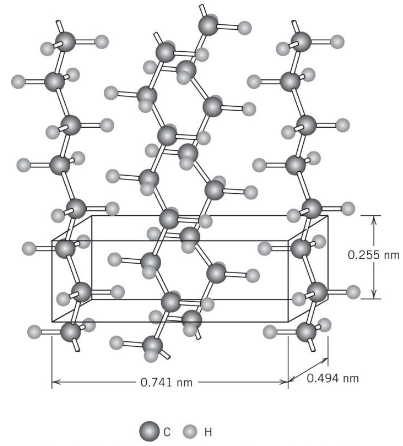


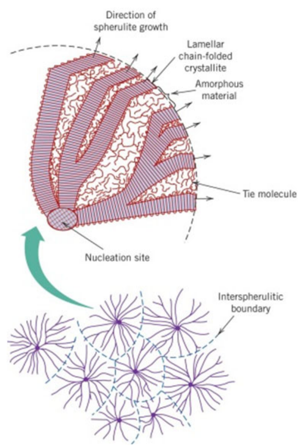
- Sulfur increases number of cross bonds

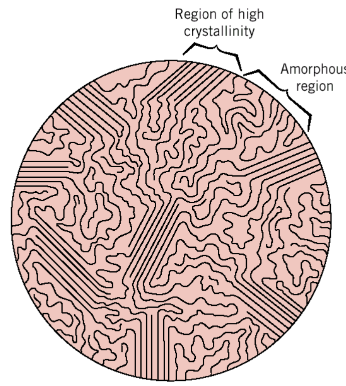
Semi-crystalline polymers

- Both amorphous and crystalline regions
- Crystalline regions act as cross links
- Maximum crystallinity about 80%
- Spherulite

- Properties
  - Higher density
  - Higher melting temperature
  - Mechanically stronger
  - Not translucent

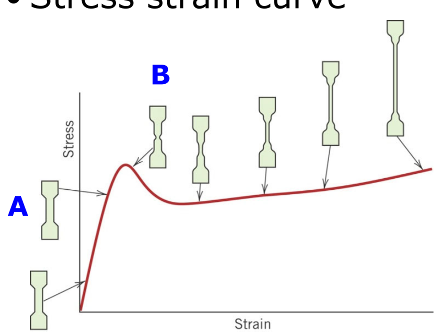






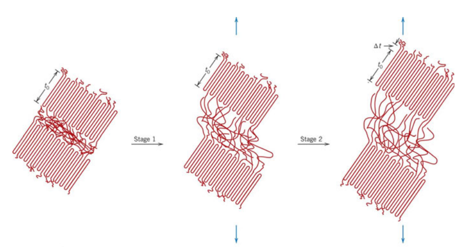
Mechanical properties of semi-crystalline polymers

- Stress strain curve

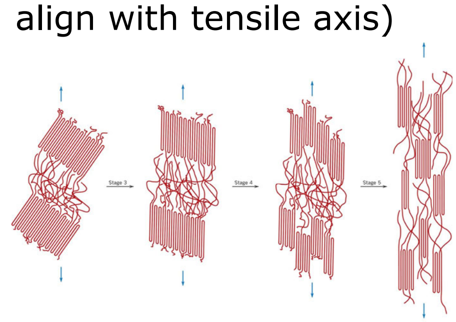


- Stretching of chains
- Re-orientation of crystalline blocks
- Alignment with tensile axis
- Hardening suppresses further necking

A Elastic deformation

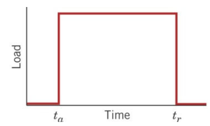


B Plastic deformation (chains align with tensile axis)

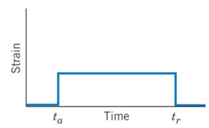


Mechanical properties of amorphous polymers Time-dependent behavior

- Stress (imposed, action)

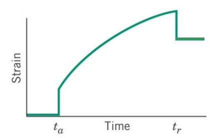


- Strain (reaction)
  - elastic

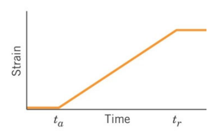


$$\tau = G\gamma$$

  - viscoelastic



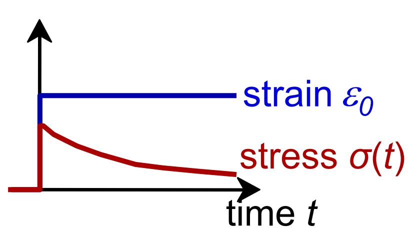
  - viscous



$$\tau = \eta\dot{\gamma}$$

Mechanical properties of amorphous polymers

- Small strain
- Stress decreases with time



- Stress relaxation

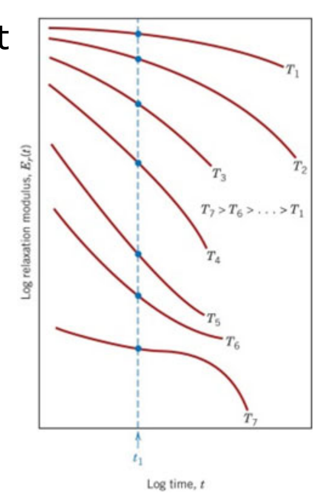
- Time dependent elastic modulus

$$E_r(t) = \frac{\sigma(t)}{\varepsilon}$$

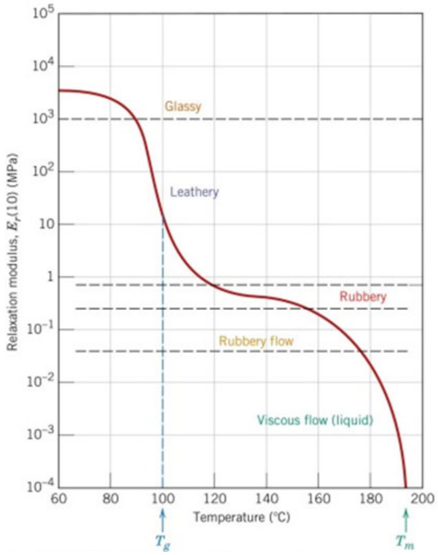
- Relaxation modulus

$E_r(10\ \text{s})$

- Temperature sensitive



Elasticity modulus / Relaxation modulus

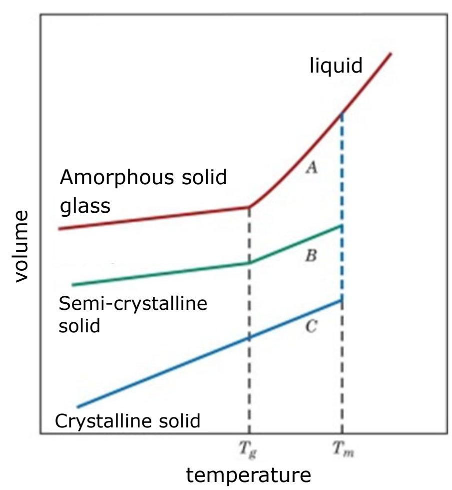


elastic (high E)	Polystyrene, Polyethylene, Polypropylene, PVC
viscoelastic	
elastic (low E)	Polybutadiene, Rubber
viscoelastic	
viscous	Silicone oil

Glass transition temperature   Melting temperature

Glass transition

- Normally: discontinuous phase transition from liquid to crystalline solid
- Glass transition: continuous transition from liquid to amorphous solid
- Glass transition temperature T_g



Glass transition

- Glass transition temperature T_g between rubber and glass
- T_g depends on chain flexibility
- high T_g for stiffer chains
  - Large side groups
  - Strong secondary bonds
  - Double bonds in chain
  - Many side branches (few branches only lower T_g)
  - High molar mass

Material	*Glass Transition Temperature (°C)*	*Melting Temperature (°C)*
Polyethylene (low density)	−110	115
Polytetrafluoroethylene	−97	327
Polyethylene (high density)	−90	137
Polypropylene	−18	175
Nylon 6,6	57	265
Poly(ethylene terephthalate) (PET)	69	265
Poly(vinyl chloride)	87	212
Polystyrene	100	240
Polycarbonate	150	265

Melting temperature follows same trends

$$T_g \propto (0.5 - 0.8) T_m$$

Rule of thumb

Except in case of branching as side branches always lower T_m