Materials-and-Production-Engineering-Lecture Materials Science - Lecture on Real Structures and Properties

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

Objectives

- Defects in crystals
- Plasticity
- Basics of mechanical properties

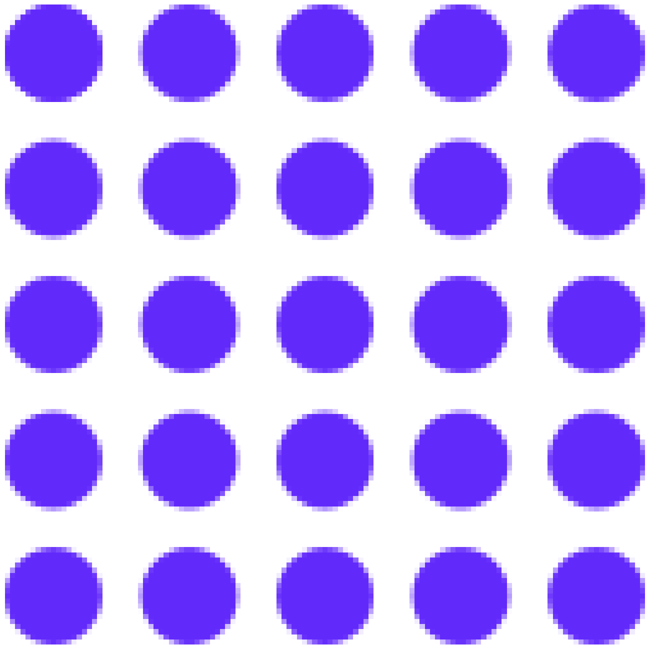
Real Structure of Crystals

Lattice Defects

- Zero-dimensional defects (point defects): vacancies, interstitial atoms, interstitial foreign atoms, substitutional foreign atom
- One-dimensional defects (line defects): dislocations
- Two-dimensional defects (surface defects): stacking faults, grain boundaries, subgrain boundaries, phase boundaries

Zero-dimensional Defects

- What are the possible variants?



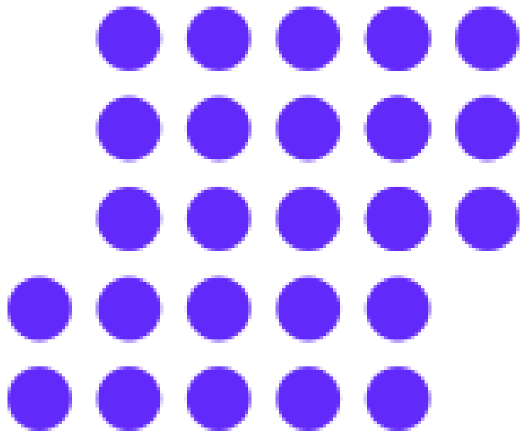
Foreign Atoms

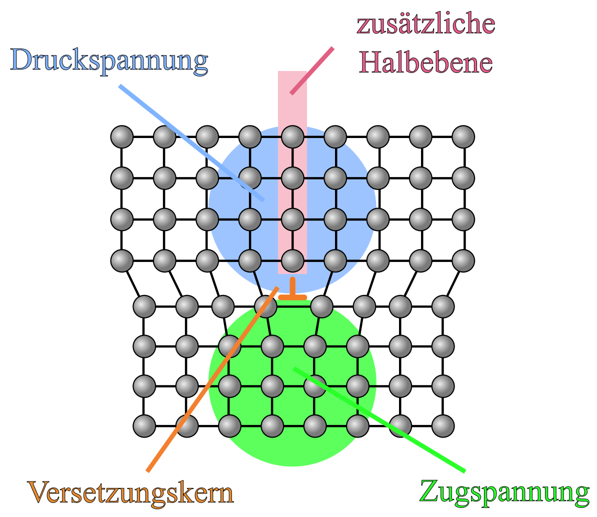
- How can foreign atoms be used?

Dislocations

Dislocations occur

- during crystal growth
- due to residual stresses
- through plastic deformation

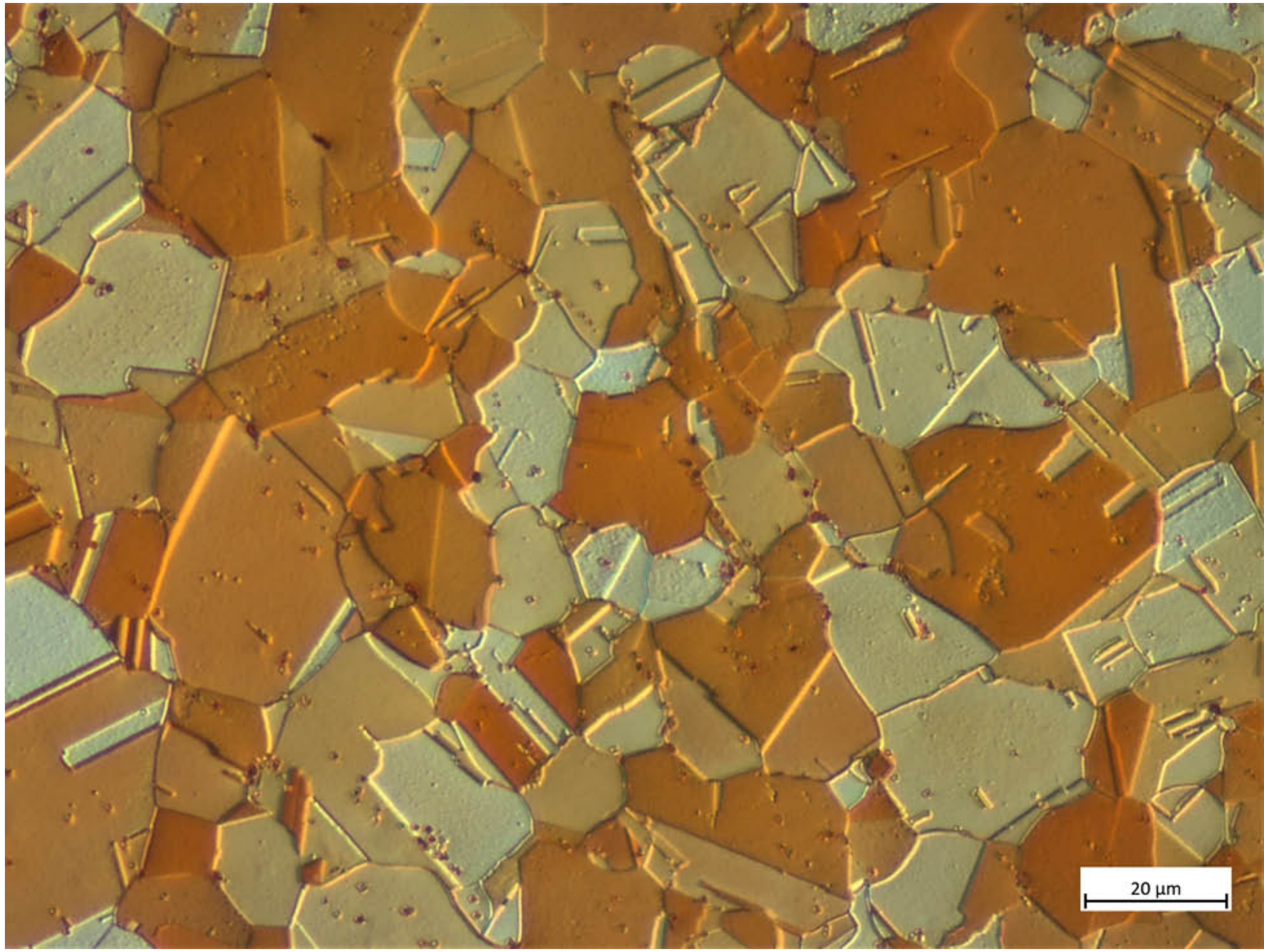




Two-dimensional Defects - Grain Boundaries

- Grain boundaries
- Phase boundaries
- Subgrain boundaries

Script



Plasticity

Good or Bad?

Examples

High plasticity:

- Modeling clay
- Wet clay
- Metals and metal alloys with a suitable atomic lattice:
    - glowing steel in forging
    - cold forming of sheets

Low plasticity:

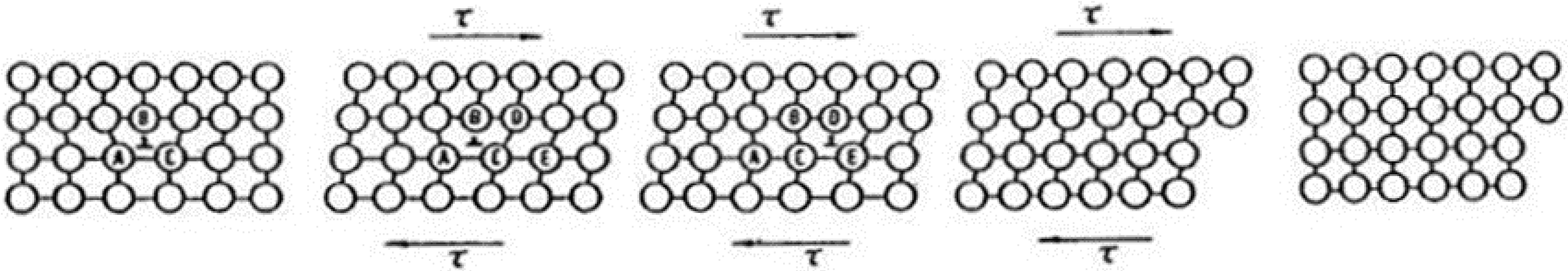
- Rubber
- Ceramics
- Fiber-reinforced composites (epoxy-glass fiber or epoxy-carbon fiber)

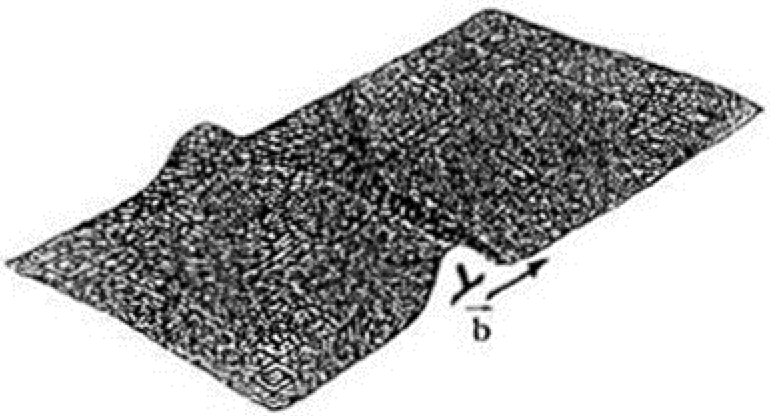
Plasticity - Single Crystal

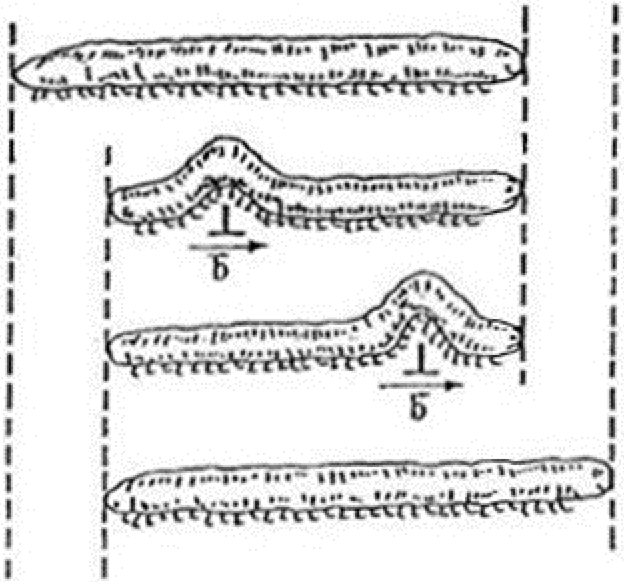
The plastic deformation of a crystal mainly occurs through the sliding of atomic layers along certain crystallographic planes and directions under the influence of shear stress.

- The slip system consists of a slip plane and a slip direction.
- Critical shear stress ($\tau_{Cr} \approx G/10$ - estimate or theoretical shear strength)
- Reality is ~100 times lower due to dislocations

Image







Plastic Deformation of Polycrystalline Material

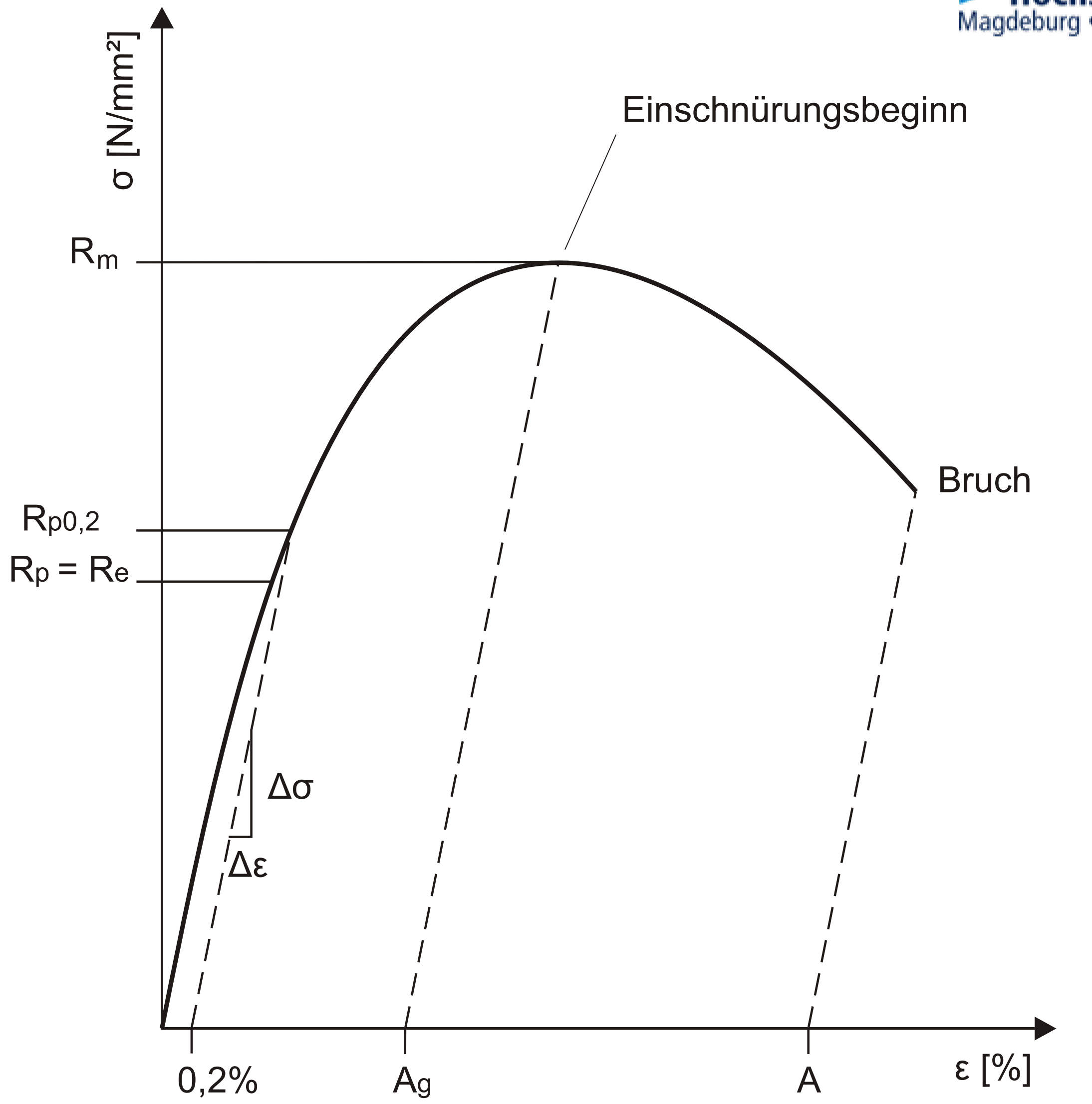
- Micro- and macroplasticity
  - Plastic deformation starts at "unfavorable" orientations
- Grain boundaries
  - Barrier to dislocation motion
  - At high temperatures, grain boundaries can slide (creep)
  - Targeted manufacturing can increase toughness through grain boundaries
- Heterogeneity
  - Multiphase materials
  - Inhomogeneous distribution of stresses and deformations
- Anisotropy

Polycrystal Plasticity

Example from a simulation

Yield Strength

- R_m - tensile strength
- R_e - yield strength
- Offset yield strength or elastic limit $R_{p0.2}$
  - After loading and unloading, 0.2% strain remains
- Offset yield strength is used as a substitute for yield strength

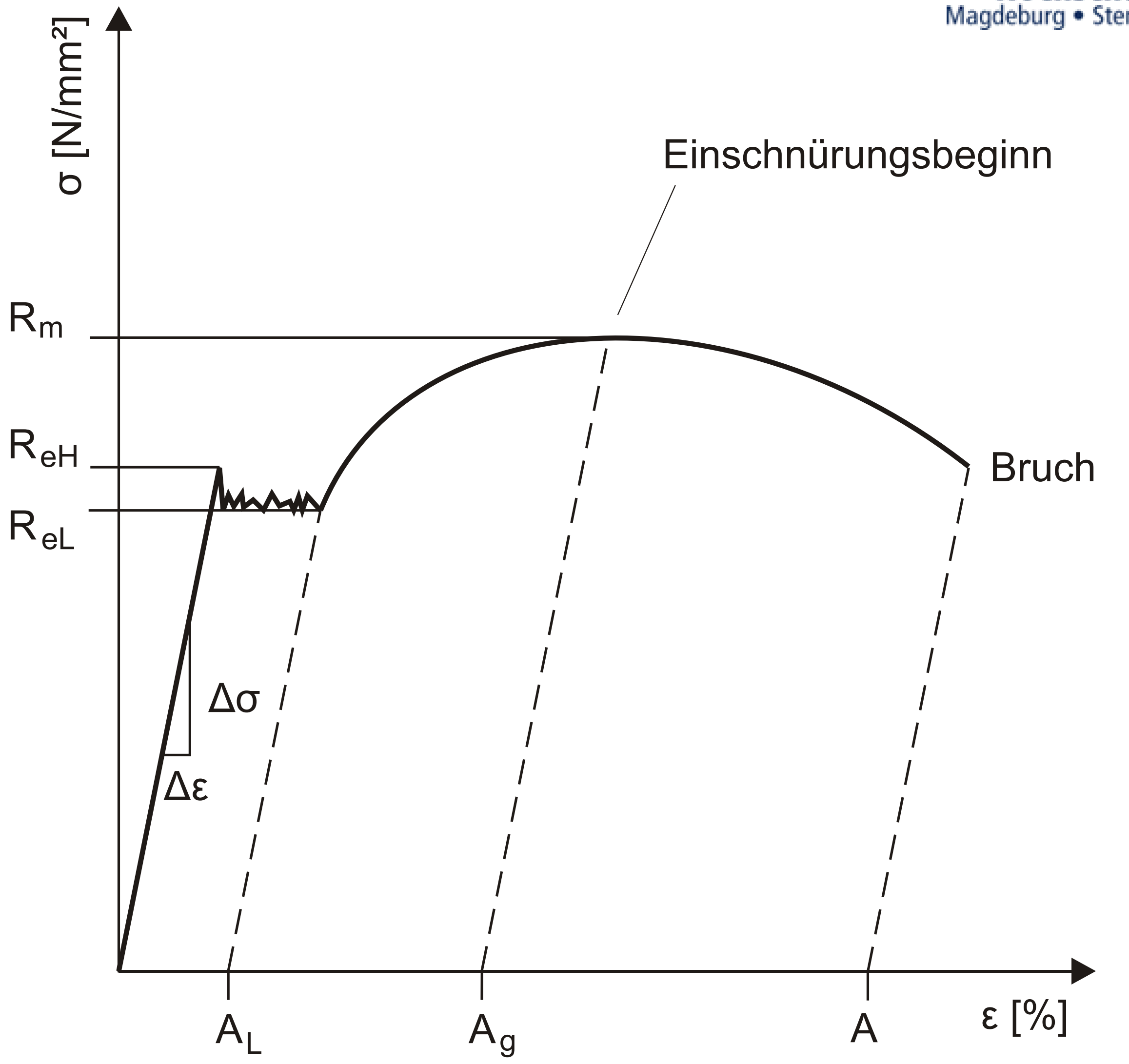


Yield Strength

- Upper yield strength R_{eH}
- Lower yield strength R_{eL}

> Jagged area: Lüders region

Example video



Plasticity - Forming

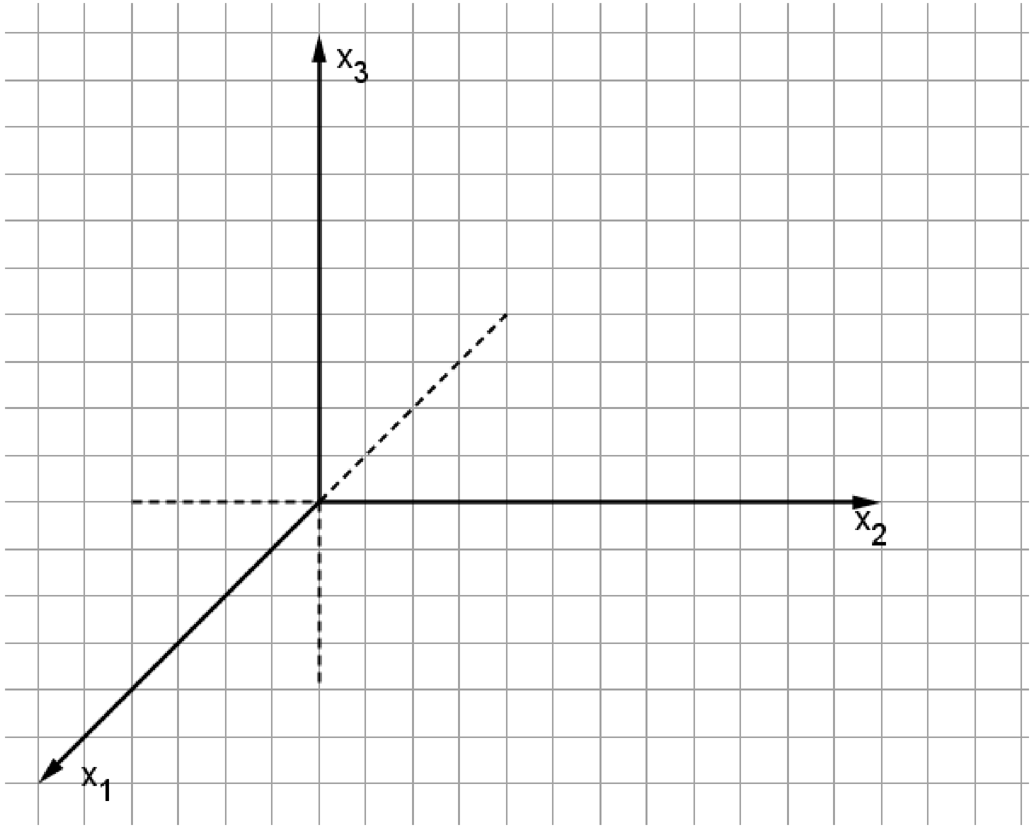
- Deep drawing principle
- Deep drawing in reality

Material Properties

What are material properties?

Symmetry

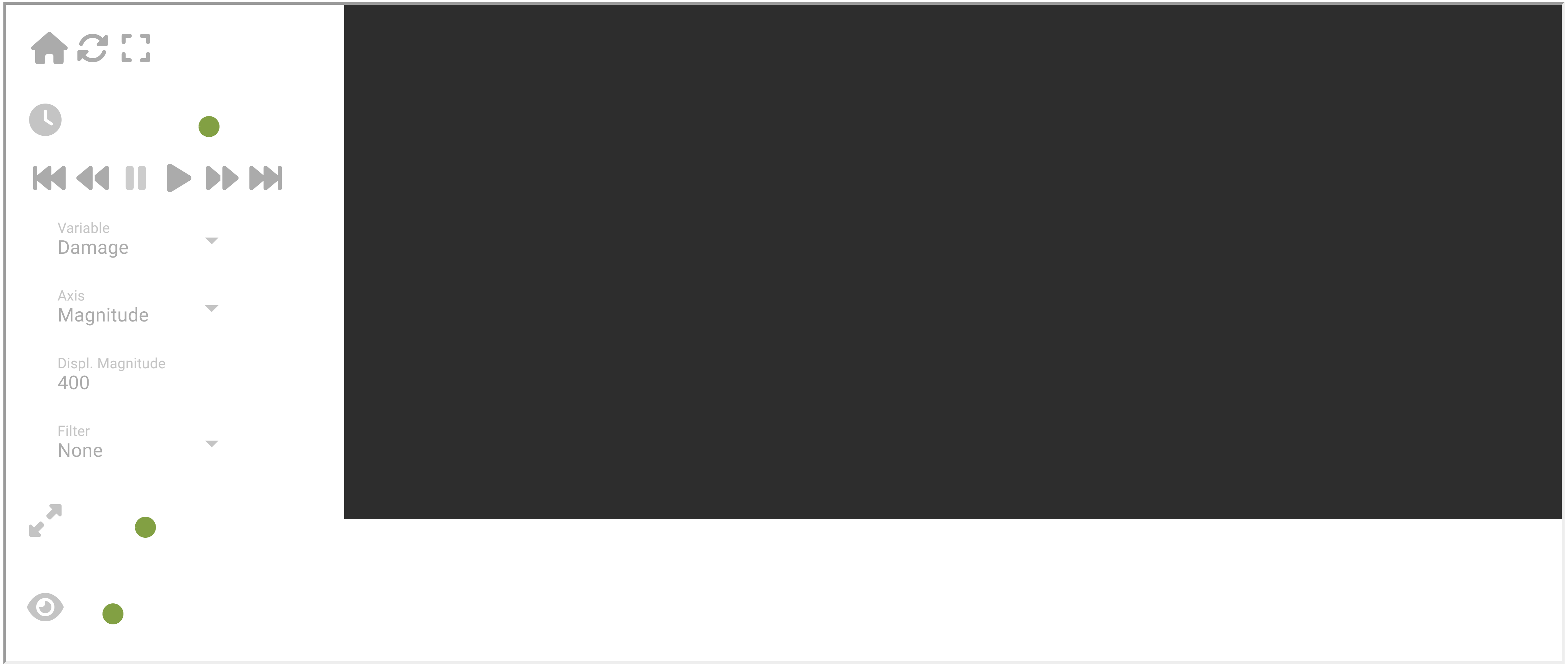
- Isotropy
- Transverse Isotropy
- Orthotropy
- …
- Anisotropy



Mechanical Properties

- **Reversible** deformation, where immediately or after a certain time following the application of external load, the deformed material returns to its original shape: elastic and viscoelastic deformation.
- **Irreversible (permanent)** deformation, where the shape change remains even after the external load is removed: plastic and viscous deformation.
- Fracture, i.e., separation of the material caused by the formation and propagation of cracks.

Simulation Example



Concept of Stress - Strain

- Geometry-independent characteristics
- How can one determine a characteristic that is defined solely by the material?
- Example: Density

Elasticity

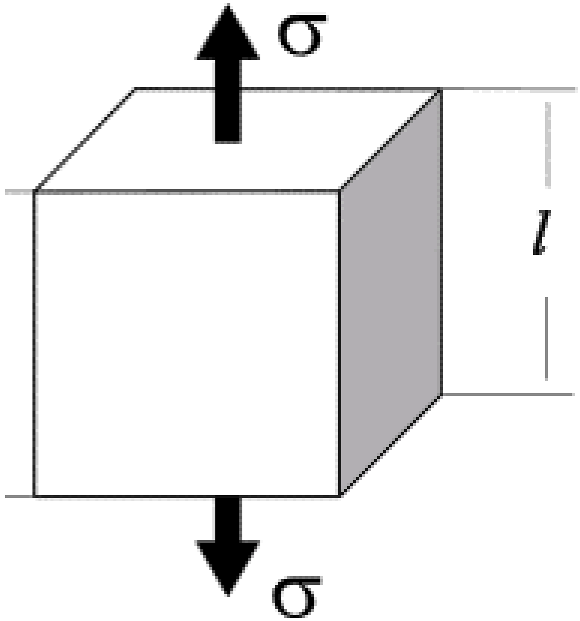
- Reversible, energy-preserving
- Hooke's Law 1D

  Normal stress $\sigma = E\varepsilon$

  Shear stress $\tau = G\gamma$

Basics

- Normal strain [-]
  $\varepsilon_{mechanical} = \frac{l - l_0}{l_0}$
- Normal stress $\left[\frac{N}{m^2}\right]$, $[Pa]$
  $\sigma = \frac{F}{A} = E\varepsilon$
  E - Elastic modulus, Young's modulus $\left[\frac{N}{m^2}\right]$



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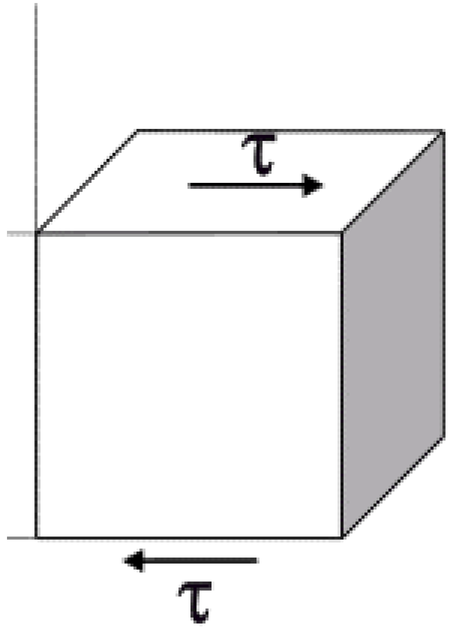
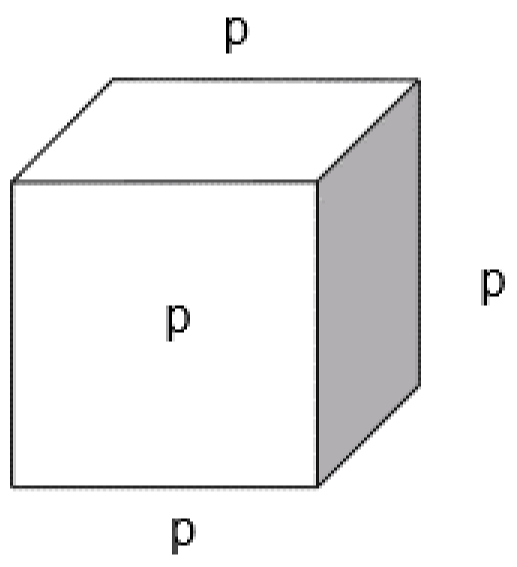
Basics

- Shear strain [-]
  $\varepsilon = \frac{1}{2}(\frac{u_x}{l_0} + \frac{u_y}{b_0}) = \frac{\gamma}{2}$
- Shear stress $\left[\frac{N}{m^2}\right]$, $[Pa]$
  $\tau = \frac{F_s}{A} = G\gamma$
- Normal and shear stresses are not compatible, leading to the concept of equivalent stresses -> Engineering Mechanics
- G - Shear modulus $\left[\frac{N}{m^2}\right]$



Basics

- Poisson's ratio [-]
  $\nu = -\frac{\varepsilon_y}{\varepsilon_x}$
  for homogeneous materials $0 \leq \nu \leq 0.5$
  for heterogeneous materials, other configurations are possible
- Bulk modulus $K = \frac{E}{3(1-2\nu)}$
- Shear modulus $K = \frac{E}{2(1+\nu)}$



Material Examples

Material	E [GPa]	G [GPa]	$\nu [-]$
Unalloyed steel	200	77	0.30
Titanium	110	40	0.36
Copper	120	45	0.35
Aluminum	70	26	0.34
Magnesium	45	17	0.27
Tungsten	360	130	0.35
Cast iron with lamellar graphite	120	60	0.25
Brass	100	35	0.35

Stiffness

- How are material properties related to stiffness?

Image reference

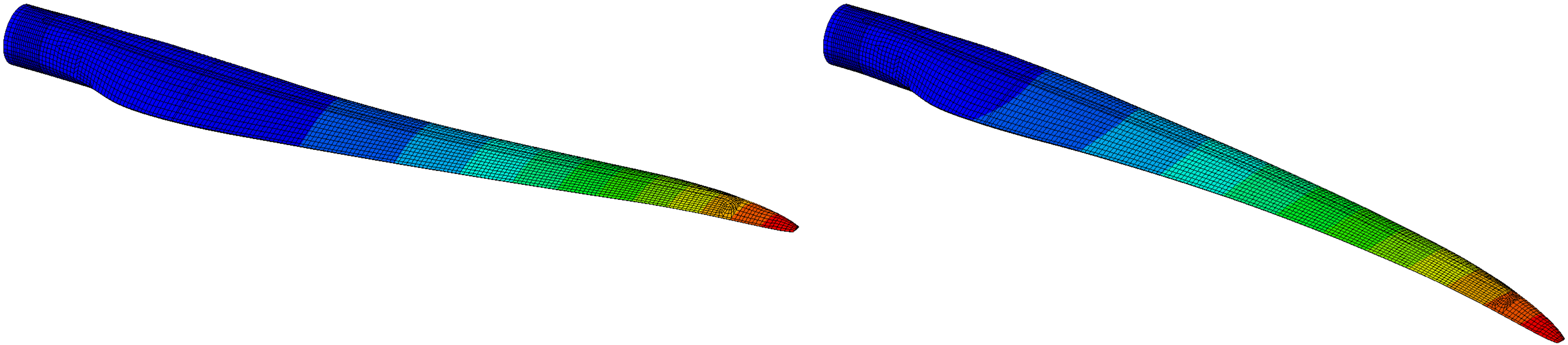


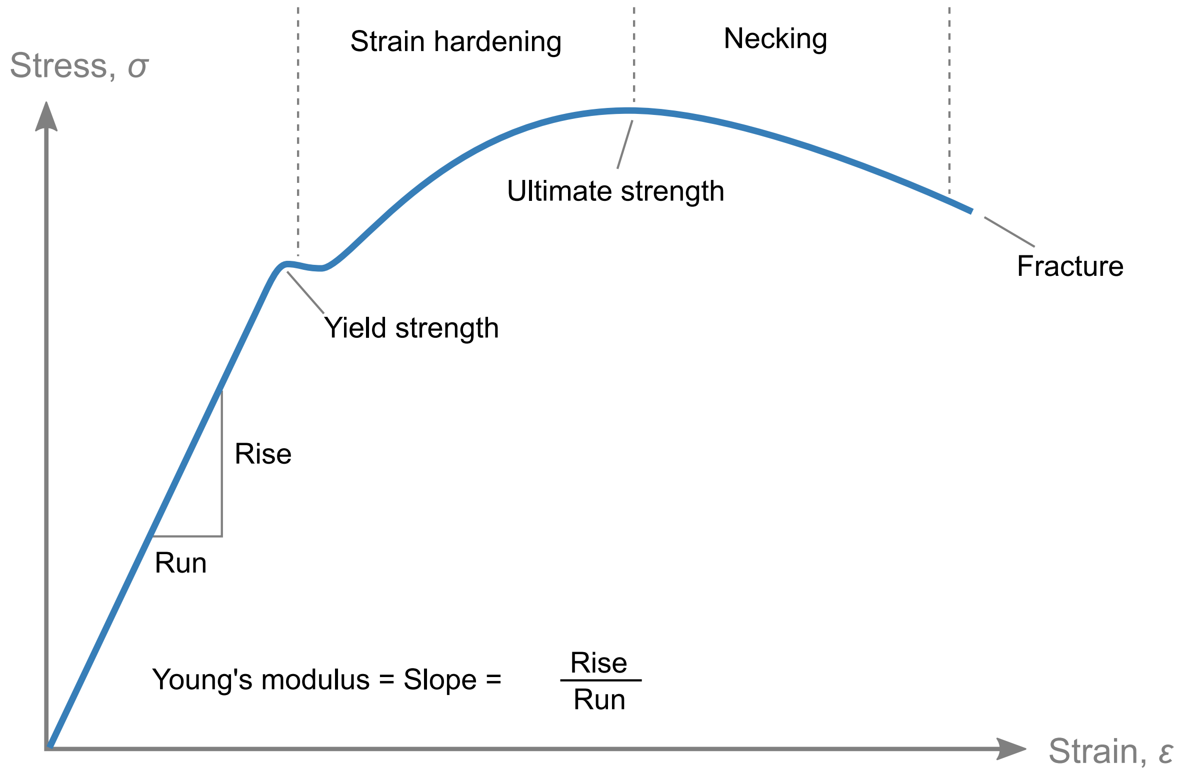
Image reference

Strength

The strength of a material describes its ability to withstand mechanical loads before failure occurs and is expressed as mechanical stress $[N/m^2]$. Failure can involve **unacceptable deformation**, particularly **plastic (permanent) deformation**, or **fracture**.

> Important: Strength $\neq$ Stiffness

Plastic Failure

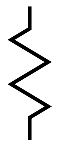


Viscous Behavior

- Reversible
- Time-dependent

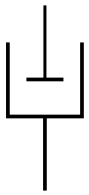
Spring model $\sigma = E\epsilon$

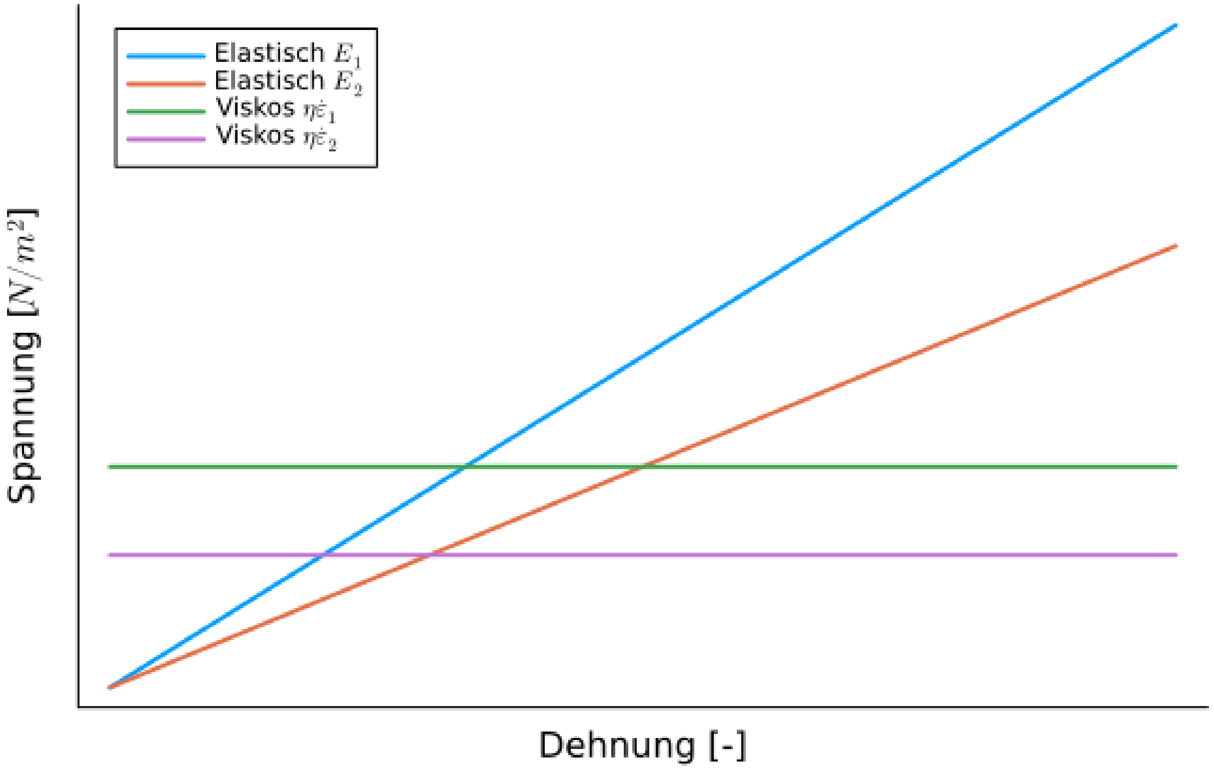
- Elastic component
- Represented by spring elements



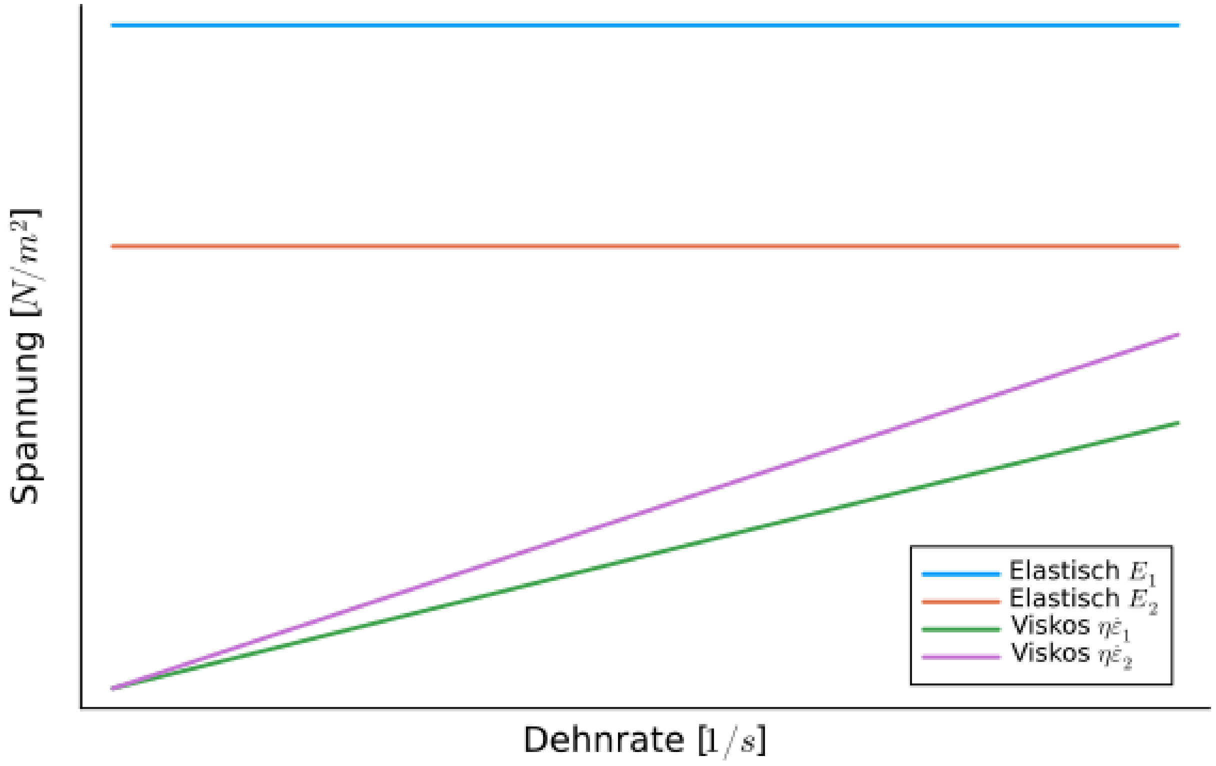
Damper $\sigma = \eta\dot{\epsilon} = \eta\frac{\partial\epsilon}{\partial t}$

- Viscous component
- Represented by damper elements





Elastisch E_1
Elastisch E_2
Viskos $\eta\dot{\varepsilon}_1$
Viskos $\eta\dot{\varepsilon}_2$
Spannung $[N/m^2]$
Dehnung [-]



Elastisch E_1
Elastisch E_2
Viskos $\eta\dot{\varepsilon}_1$
Viskos $\eta\dot{\varepsilon}_2$
Spannung $[N/m^2]$
Dehnrate $[1/s]$

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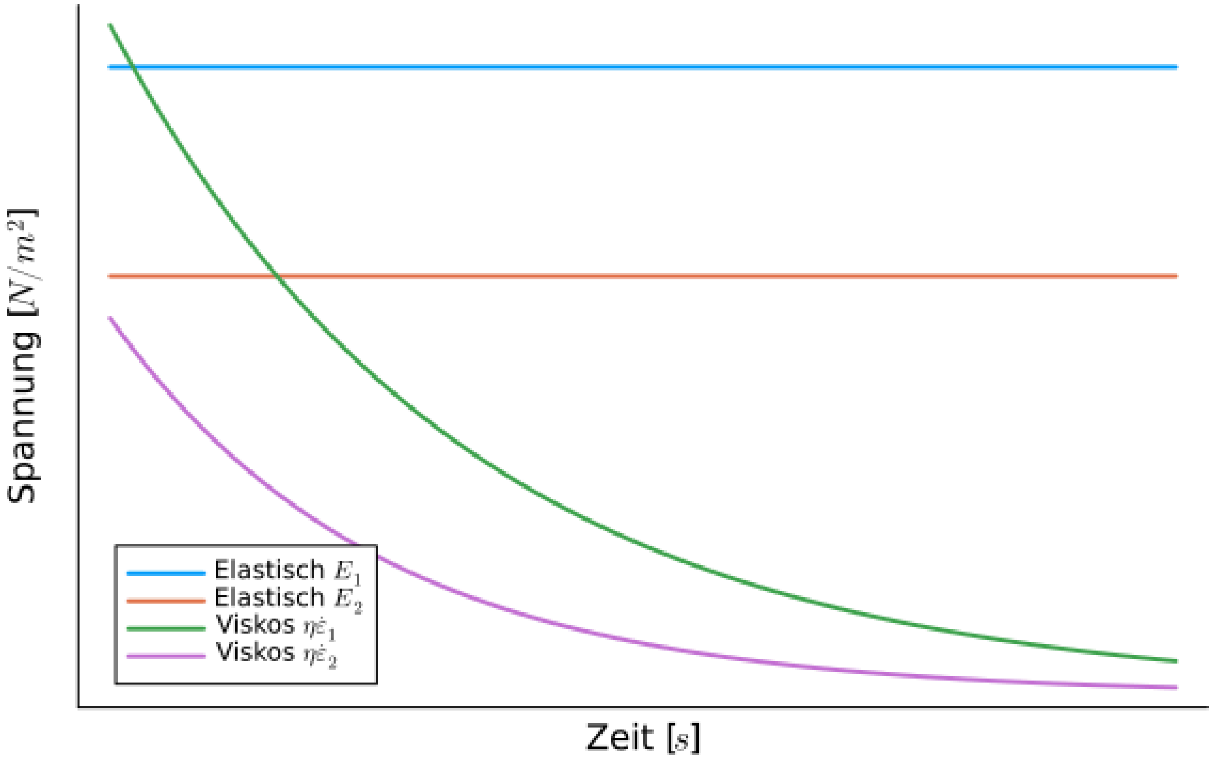

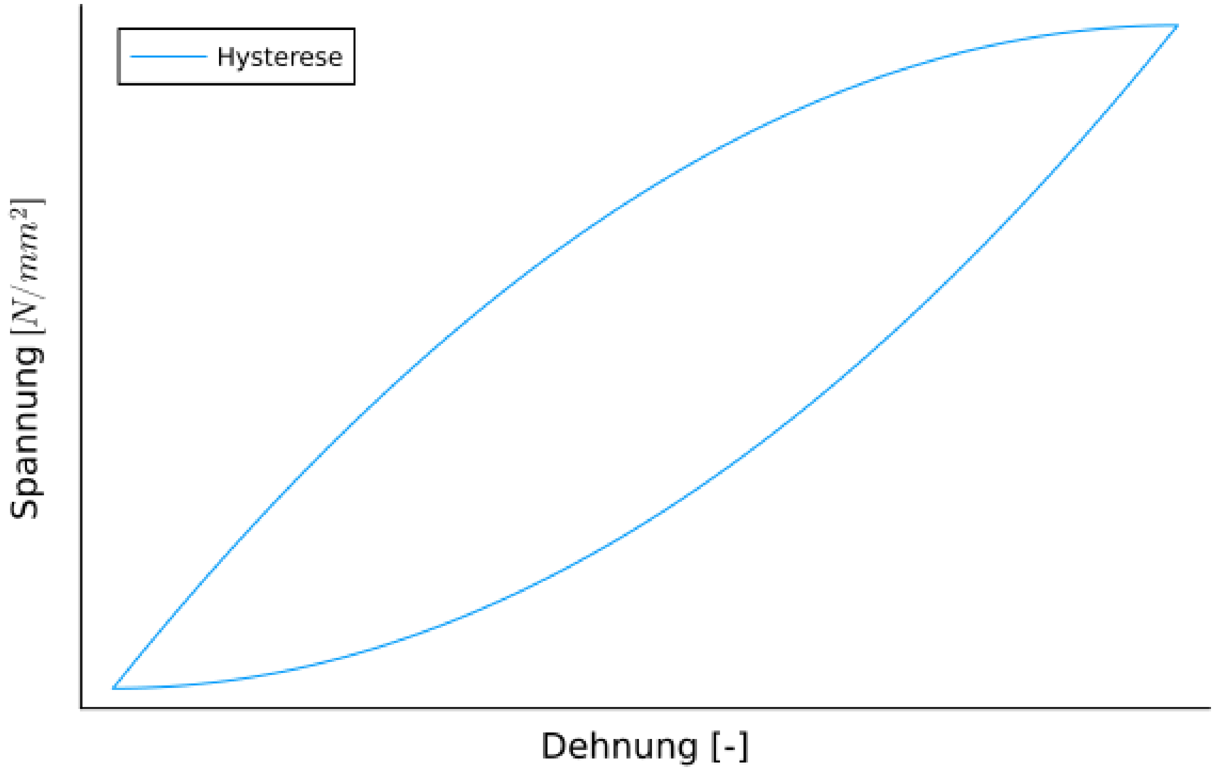

Excursion: Modeling of Materials

- Rheological models
- Consist of many springs, dampers, and other elements
- These degrees of freedom (E_i, η_i) are then fitted