Mechanical testing

How to change shape?

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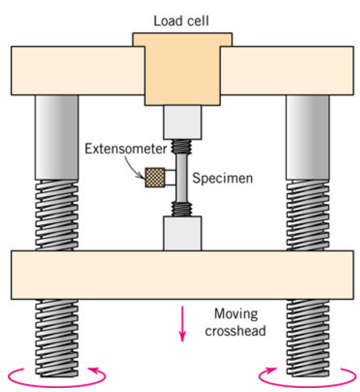
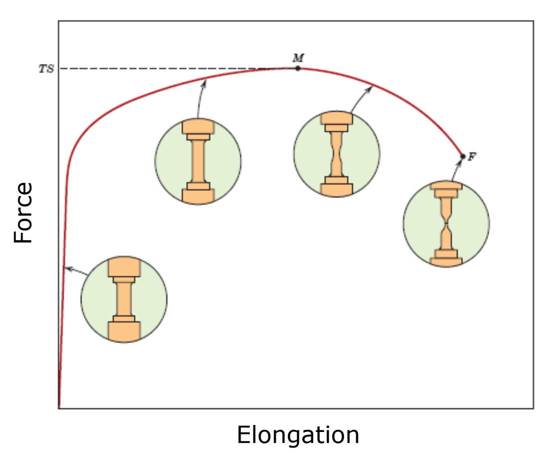
Mechanical testing – tensile test

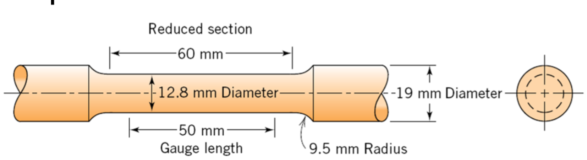
- Tensile testing



- Measurement



- Specimen



Measurement and mechanical measures

(Normal) Force F_n
- Depends on initial cross section A_0 of specimen
- (a specimen twice as thick requires twice the force)

Elongation Δl
- Depends on initial length l_0 of specimen
- (a specimen with twice the length achieves twice the elongation)

Stress

$$\sigma = \frac{F_n}{A_0}$$

Strain
(relative elongation)

$$\varepsilon = \frac{\Delta l}{l_0}$$

Engineering stress and engineering strain

- Engineering stress

$$\sigma = \frac{F_n}{A_0}$$

- Units 1 Pa = 1 N/m^2
  Usually 1 MPa = 10^6 N/m^2

- Tensile stress $\sigma > 0$
- Compressive stress $\sigma < 0$

- Engineering strain

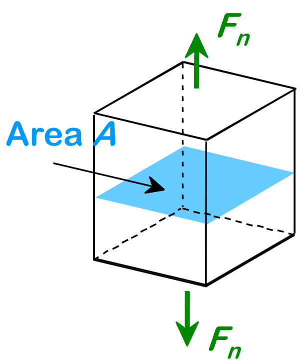
$$\varepsilon = \frac{\Delta l}{l_0} = \frac{l - l_0}{l_0}$$

- Units 1 m/m or dimensionless (%)
- Relative elongation

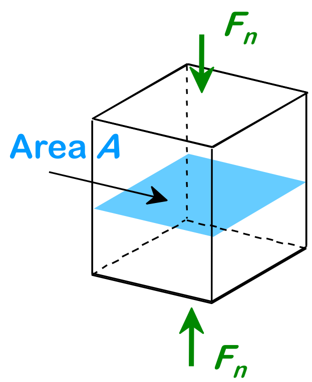
A_0 initial cross section area
l specimen length
l_0 initial specimen length
$\Delta l = l - l_0$ elongation

Stress

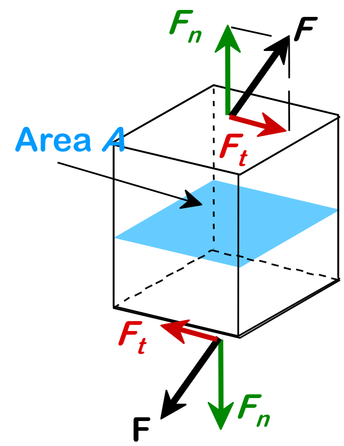
Tensile stress σ



Compressive stress σ



Shear stress τ



$$\boxed{\sigma = \frac{F_n}{A_0}}$$

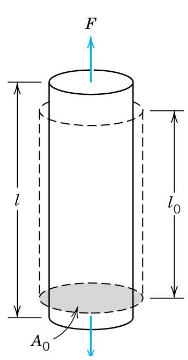
A_0 Initial cross section area
F_n Normal Force
F_t Tangential Force

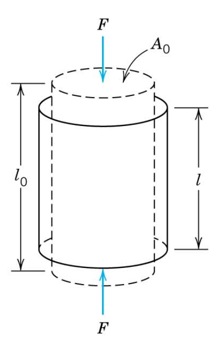
$$\boxed{\tau = \frac{F_t}{A_0}}$$

Strain

Elongation
due to tension

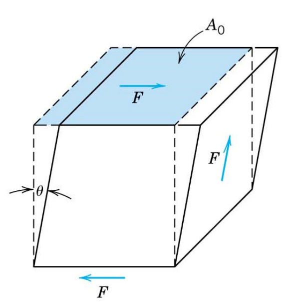
= positive strain





Contraction
due to compression

= negative strain

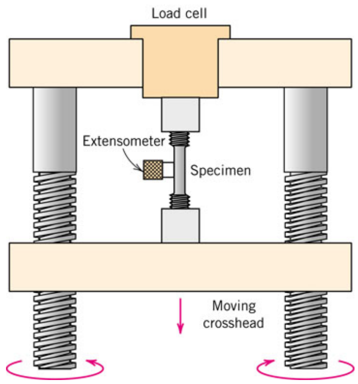


Shear strain

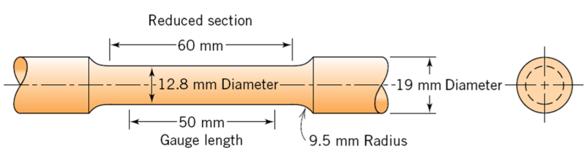
$\gamma = \tan\theta$

Mechanical testing – tensile test

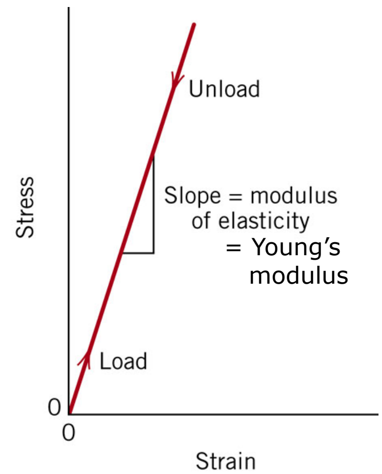
- Tensile testing



- Specimen



- Measurement



Elastic properties

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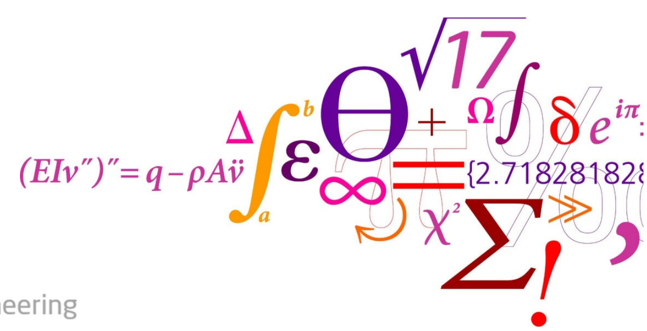
First materials law
1660 *ceiiinosssttuv*
1678 *ut tensio, sic vis*



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Elastic behavior

- Hooke's law

$$\sigma = E\varepsilon$$

ut tensio, sic vis

- Proportionality factor

Elastic modulus
Young's modulus
E-modulus

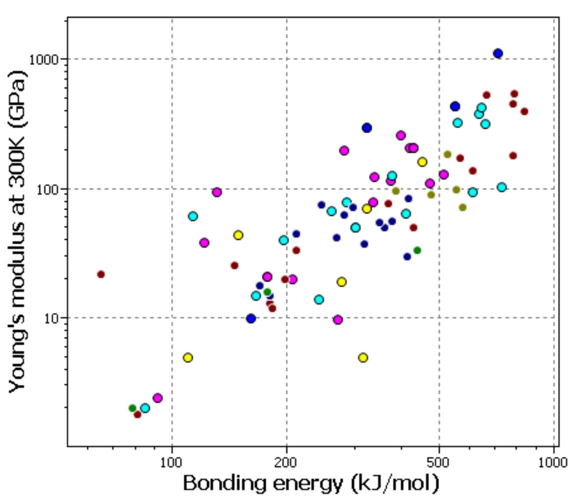
- Correlation between Young's modulus and melting temperature

	E	T_m
Pb	16 GPa	327 °C
Al	71 GPa	660 °C
Cu	130 GPa	1084 °C
Fe	210 GPa	1538 °C
W	411 GPa	3422 °C

- Both controlled by bonding energy

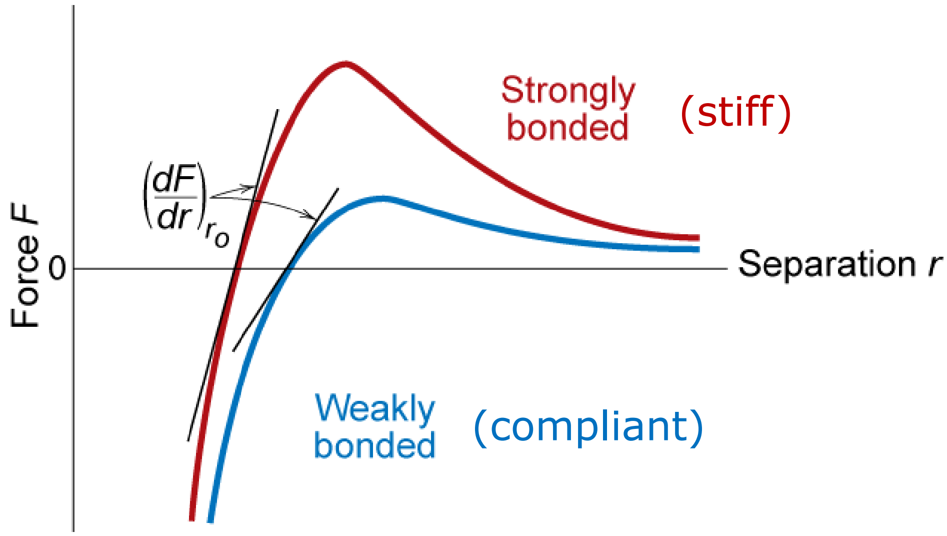
Property correlations – elements

- Young's modulus and bonding energy

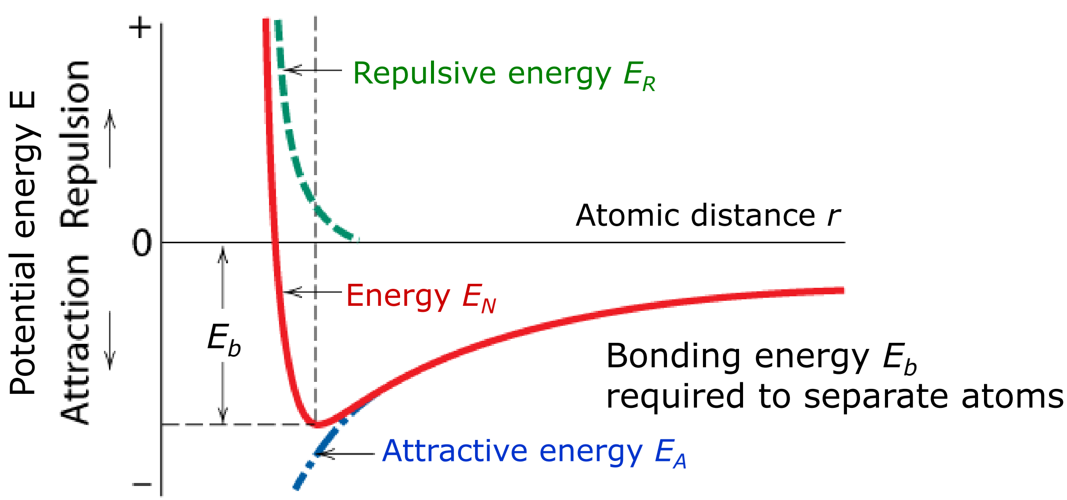


Bonding and elastic behavior

- Counteracting forces for deviations from equilibrium



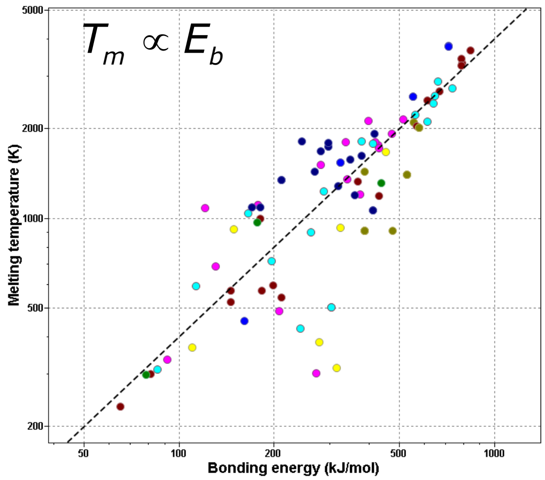
Bonding energy

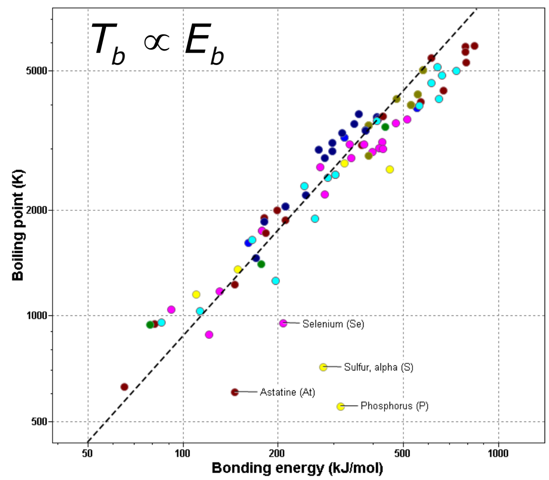


Affects materials properties
Bond energy → melting temperature (boiling temp.)
Energy profile → Elastic modulus, thermal expansion

Property correlations – elements

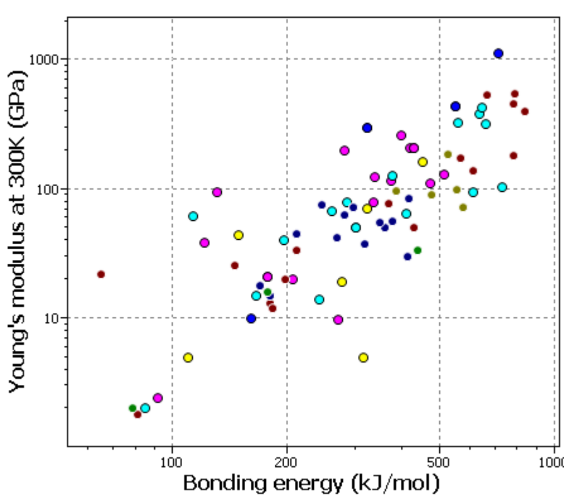
- Melting temperature and bonding energy
- Boiling temperature and bonding energy

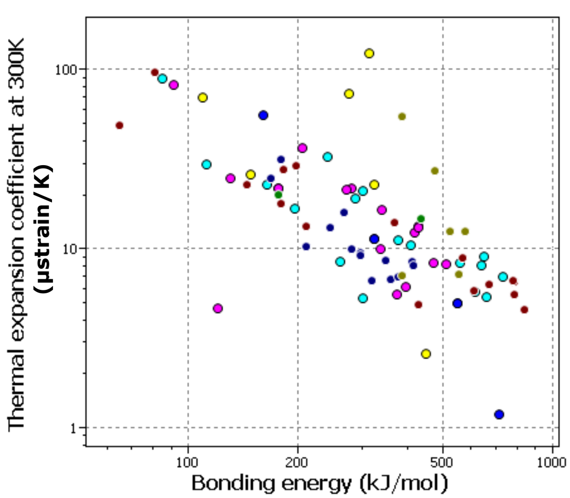




Property correlations – elements

- Young's modulus and bonding energy
- Thermal expansion coefficient and bonding energy



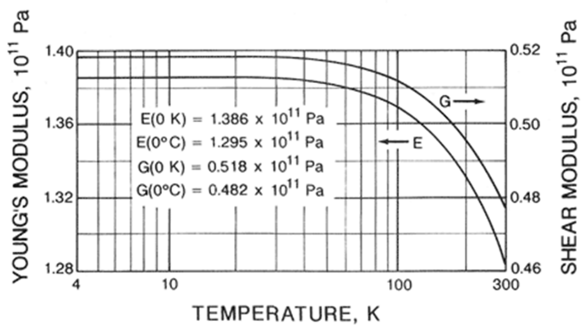


Young’s modulus and temperature

- Young’s modulus E decreases with temperature
- Reason: thermal oscillations
- Similar other elastic moduli e.g. shear modulus G

$$\tau = G\gamma$$

- Example: copper



Young’s modulus and crystallography

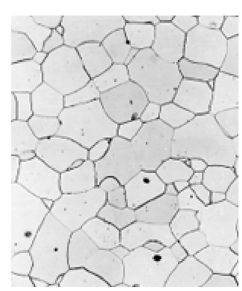
- E depends on lattice direction

	Modulus of Elasticity (GPa)		
Metal	[*100*]	[*110*]	[*111*]
Aluminum	63.7	72.6	76.1
Copper	66.7	130.3	191.1
Iron	125.0	210.5	272.7
Tungsten	384.6	384.6	384.6

- Anisotropy (usually)

$$E_{\langle 111\rangle} > E_{\langle 110\rangle} > E_{\langle 100\rangle}$$

- For most cubic lattices
- Relevant for single crystals
- Usually: polycrystals



Young's modulus of alloys (substitutional solid solutions)

- Depends on composition and alloy type
- Substitutional solid solutions
- Example: Cu Ni

Legering	E/GPa
Cu	115
CuNi10FeMn	130
CuNi25	145
CuNi30Mn1Fe3	150
CuNi44Mn1	165
Ni	207

Alternatives to solid solutions

- Intermetallic compound
  - Different crystal structure
  - Different bonds
  - Different elastic moduli
- Mixture of phases
  - Rule of mixtures
  - Young's modulus depends on spatial arrangement
  - See composites L13

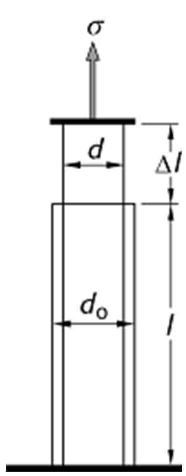
Elastic behavior – cross contraction

- Change in extension perpendicular to load

$\Delta l > 0$

$\Delta d < 0$

(in general)



- Poisson's ratio

$$\nu = -\frac{\Delta d / d_0}{\Delta l / l_0} = -\frac{\varepsilon_x}{\varepsilon_z}$$

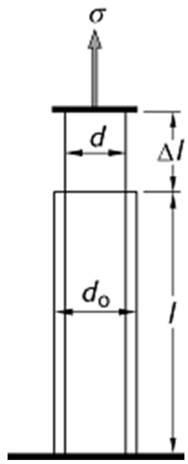
- for load along z-direction
- usually $0.25 \le \nu \le 0.35$ (most times 0.3)
- Note: volume conservation $\nu = 0.5$

Advanced material of the day: Metamaterials

- Change in extension perpendicular to load

What does a negative Poisson ratio mean?

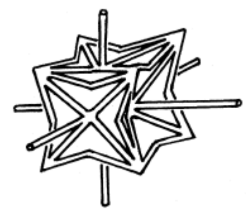
Can materials possess a negative Poisson ratio?



- Poisson's ratio

$$\nu = -\frac{\Delta d / d_0}{\Delta l / l_0} = -\frac{\varepsilon_x}{\varepsilon_z}$$

- Negative Poisson ratio
  - Auxetic materials
  - Foams



Mechanical testing – shear test

- Shear stress

$$\tau = \frac{F_s}{A_0}$$

- Shear strain

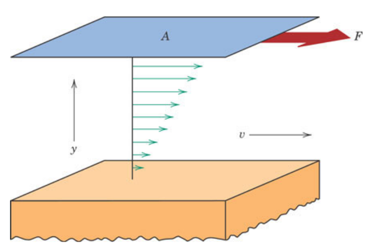
$$\gamma = \frac{\Delta x}{h_0}$$

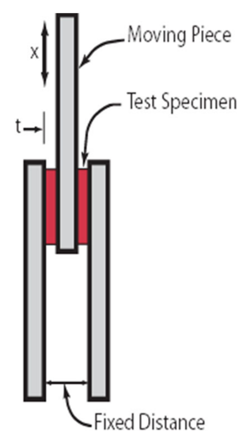
- Hooke's law

$$\tau = G\gamma$$

- Shear modulus G

- Shear test



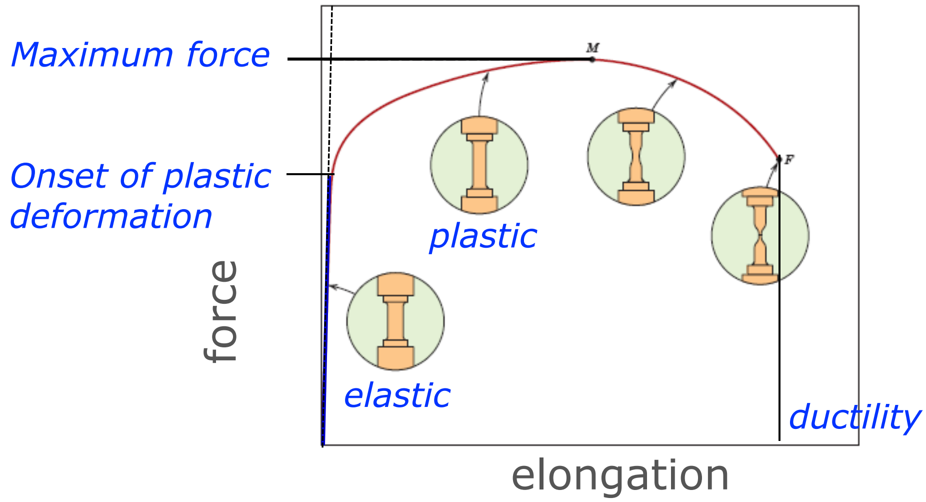


- Elastic isotropic materials

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

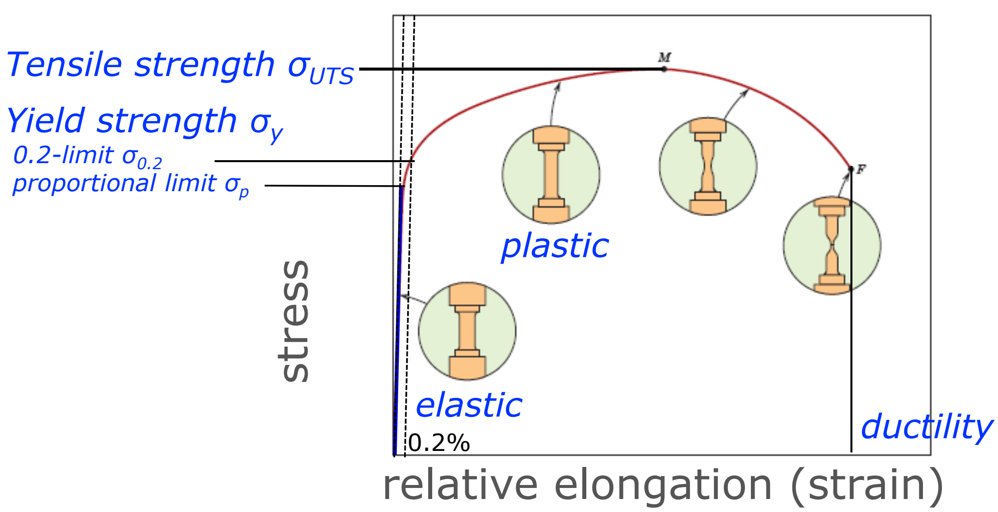
Tensile testing

- Elastic behavior - reversible
- Plastic behavior - irreversible



Tensile testing

- Elastic behavior - reversible
- Plastic behavior - irreversible



Materials selection

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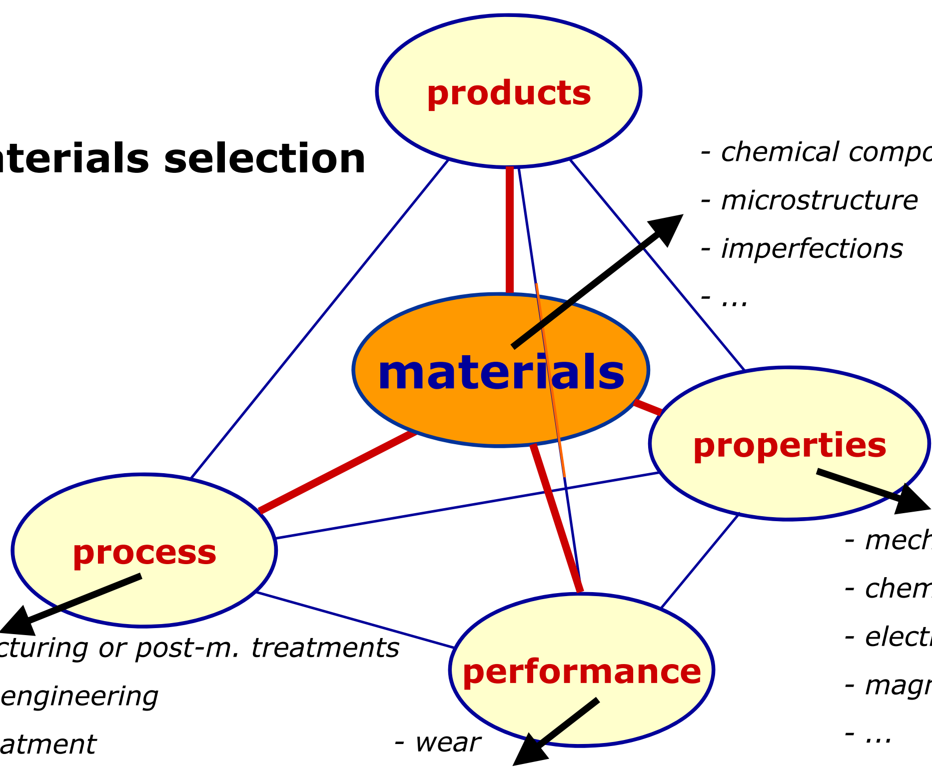
Materials selection



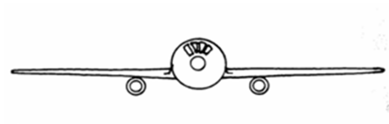
- chemical composition
- microstructure
- imperfections
- …

- mechanical
- chemical
- electrical
- magnetical
- …

- manufacturing or post-m. treatments
- surface engineering
- heat treatment
- plastic deformation
- …

- wear
- corrosion
- …

Mechanical properties



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(formerly Cambridge Engineering Selector)

Materials property data base

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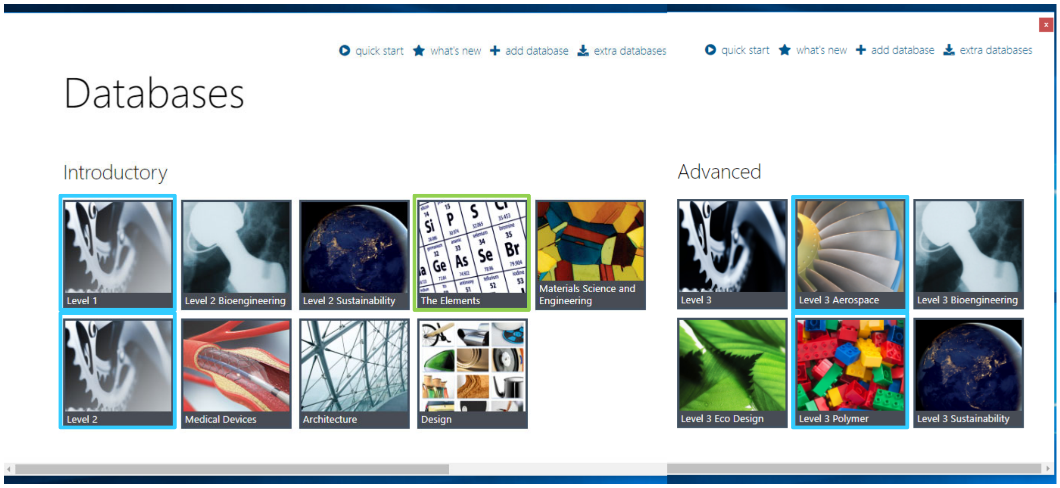
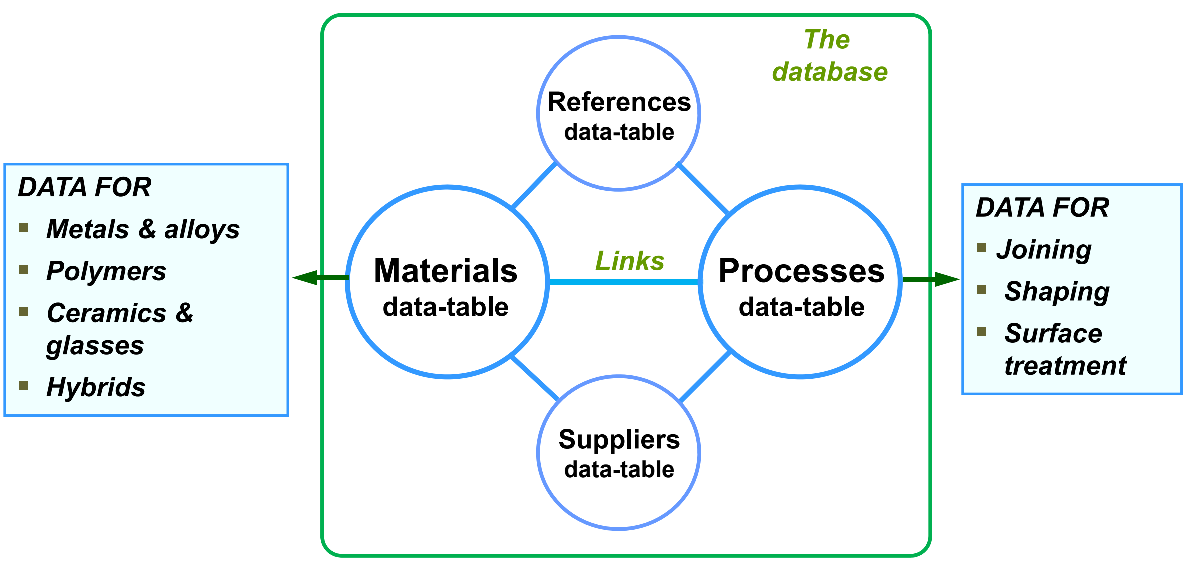
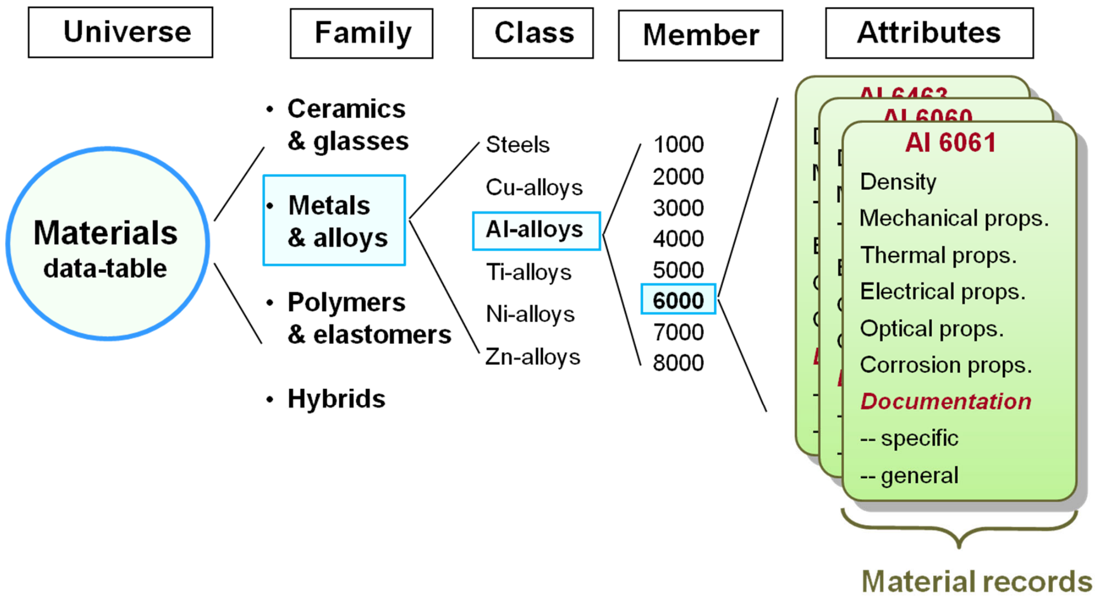
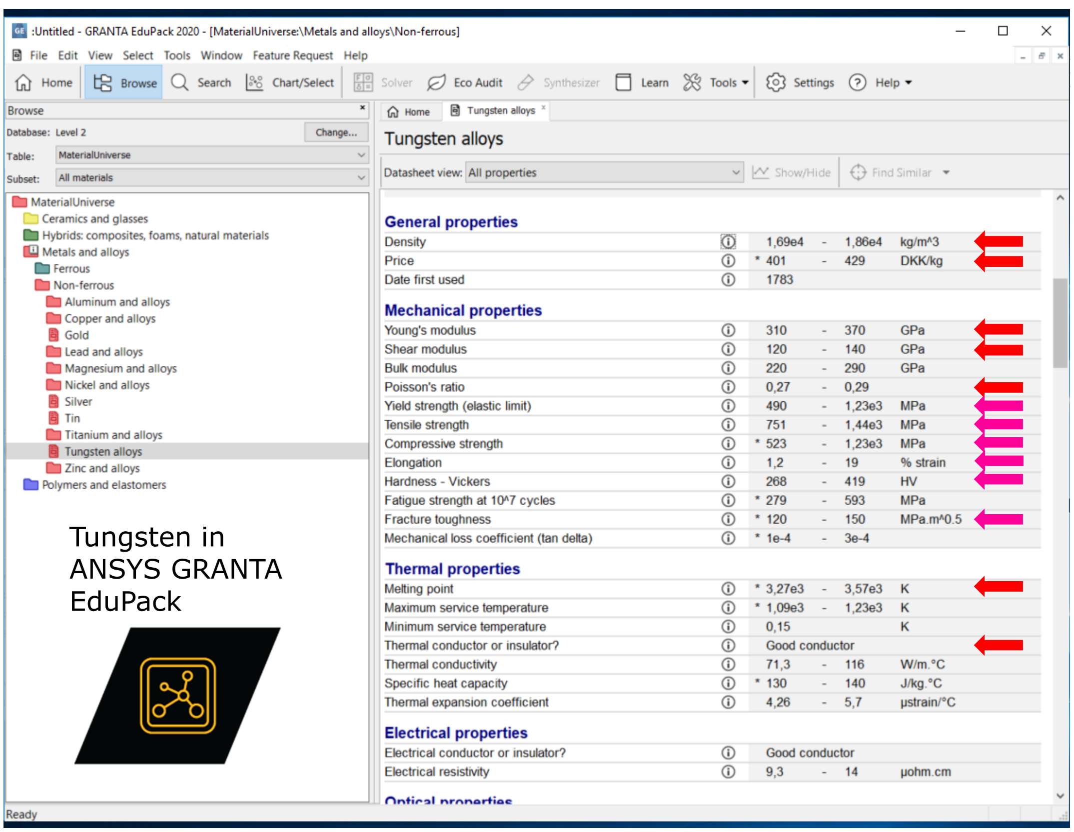


Organization of entire information



Organization of information: materials tree





General properties				
Density	1,69e4	-	1,86e4	kg/m^3
Price	* 401	-	429	DKK/kg
Date first used	1783			
Mechanical properties				
Young's modulus	310	-	370	GPa
Shear modulus	120	-	140	GPa
Bulk modulus	220	-	290	GPa
Poisson's ratio	0,27	-	0,29	
Yield strength (elastic limit)	490	-	1,23e3	MPa
Tensile strength	751	-	1,44e3	MPa
Compressive strength	* 523	-	1,23e3	MPa
Elongation	1,2	-	19	% strain
Hardness - Vickers	268	-	419	HV
Fatigue strength at 10^7 cycles	* 279	-	593	MPa
Fracture toughness	* 120	-	150	MPa.m^0.5
Mechanical loss coefficient (tan delta)	* 1e-4	-	3e-4	
Thermal properties				
Melting point	* 3,27e3	-	3,57e3	K
Maximum service temperature	* 1,09e3	-	1,23e3	K
Minimum service temperature	0,15			K
Thermal conductor or insulator?	Good conductor			
Thermal conductivity	71,3	-	116	W/m.°C
Specific heat capacity	* 130	-	140	J/kg.°C
Thermal expansion coefficient	4,26	-	5,7	µstrain/°C
Electrical properties				
Electrical conductor or insulator?	Good conductor			
Electrical resistivity	9,3	-	14	µohm.cm

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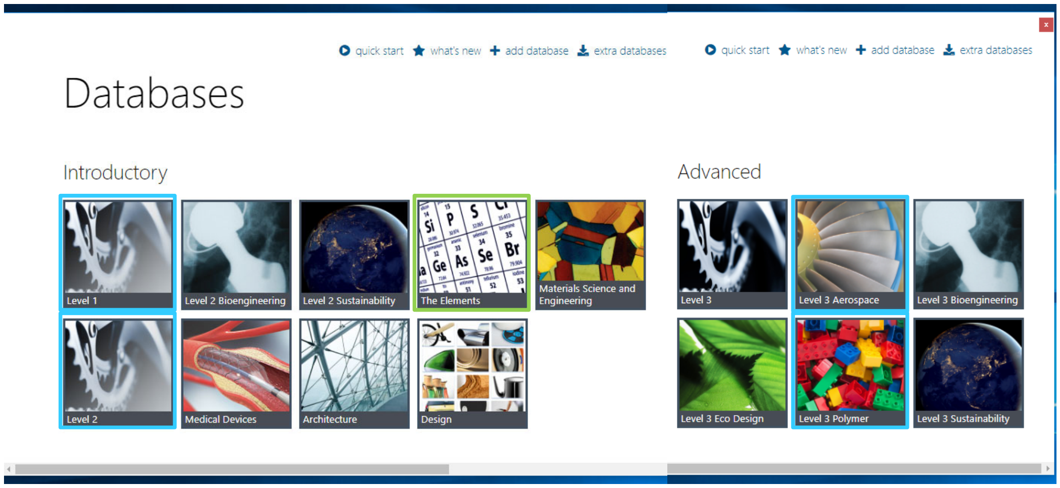
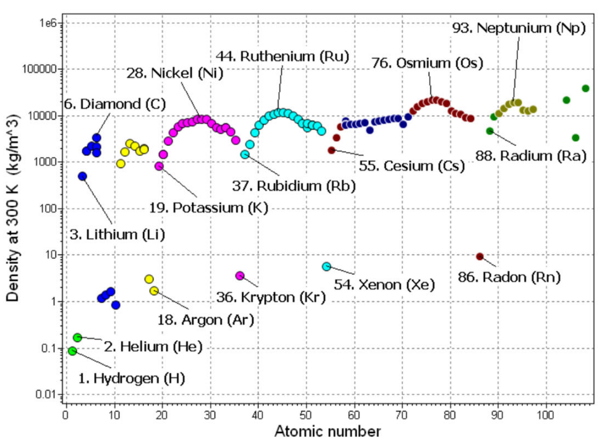
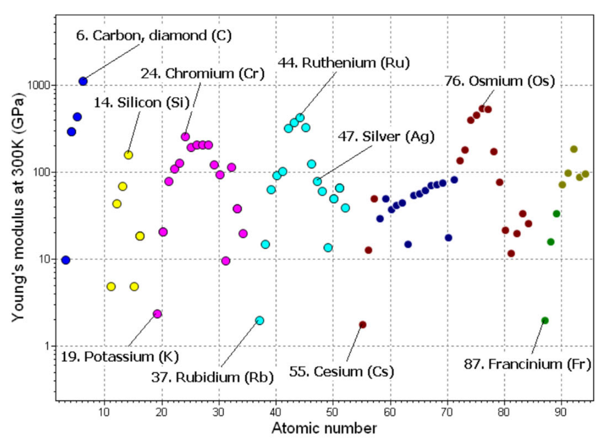
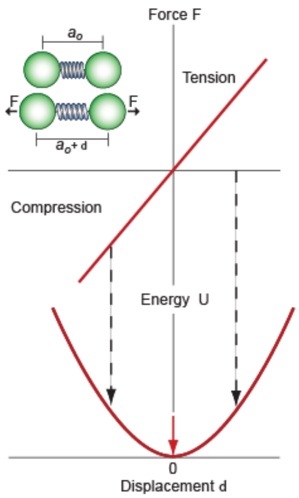


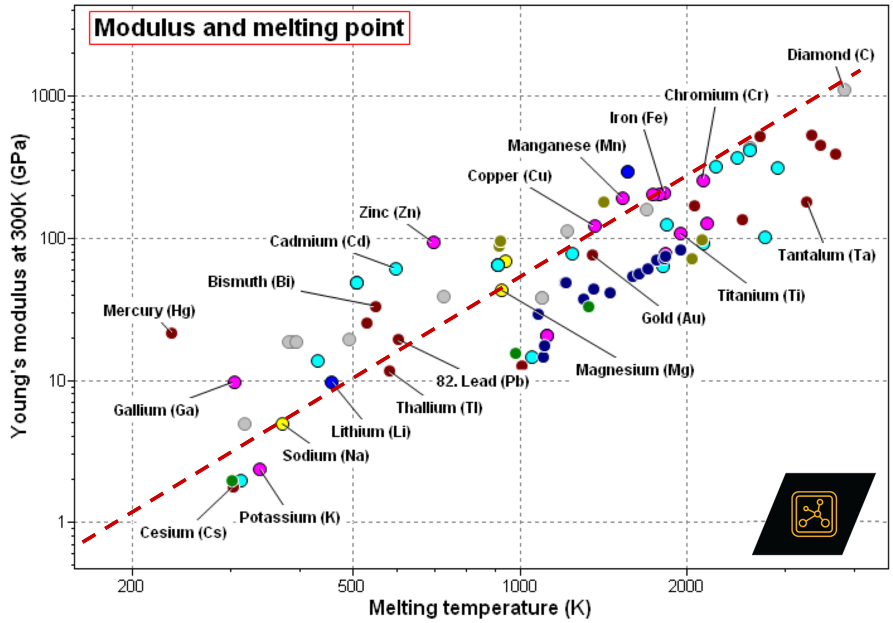
Properties of elements



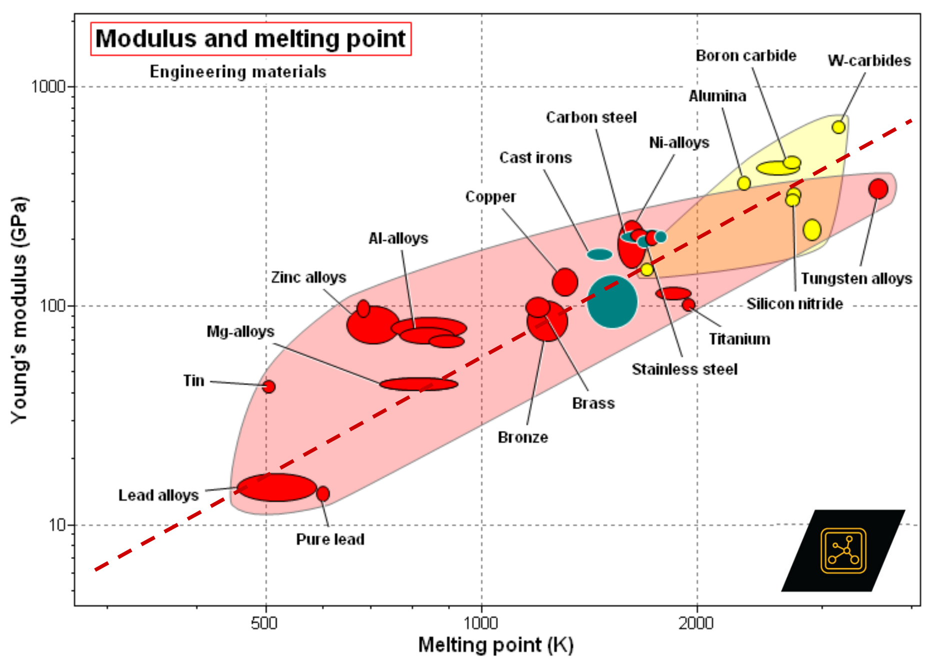


Relationship between properties - elements

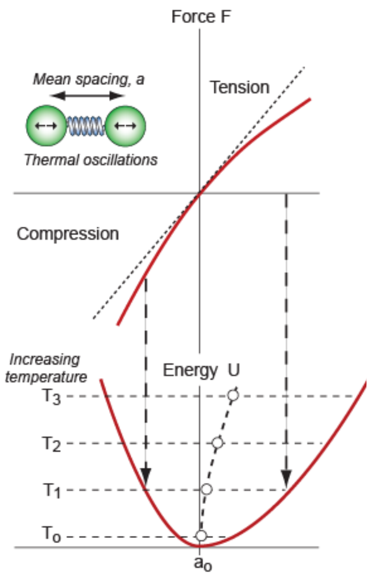


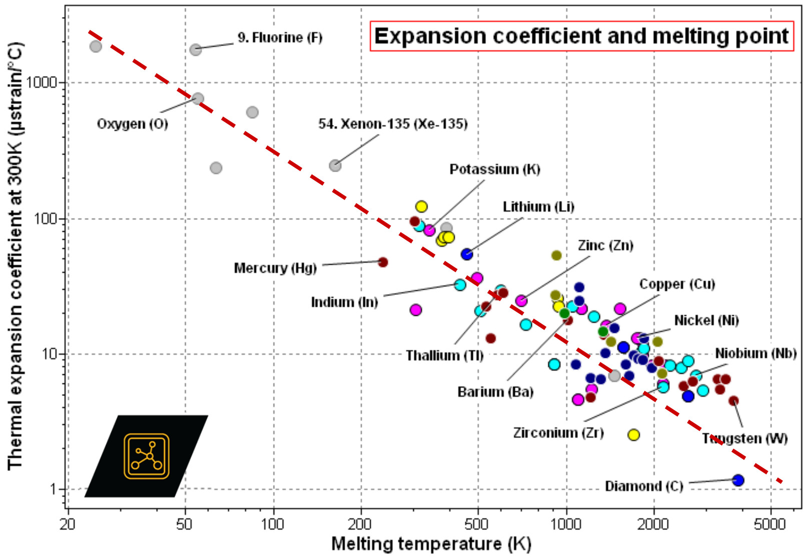


Relationship between properties - materials

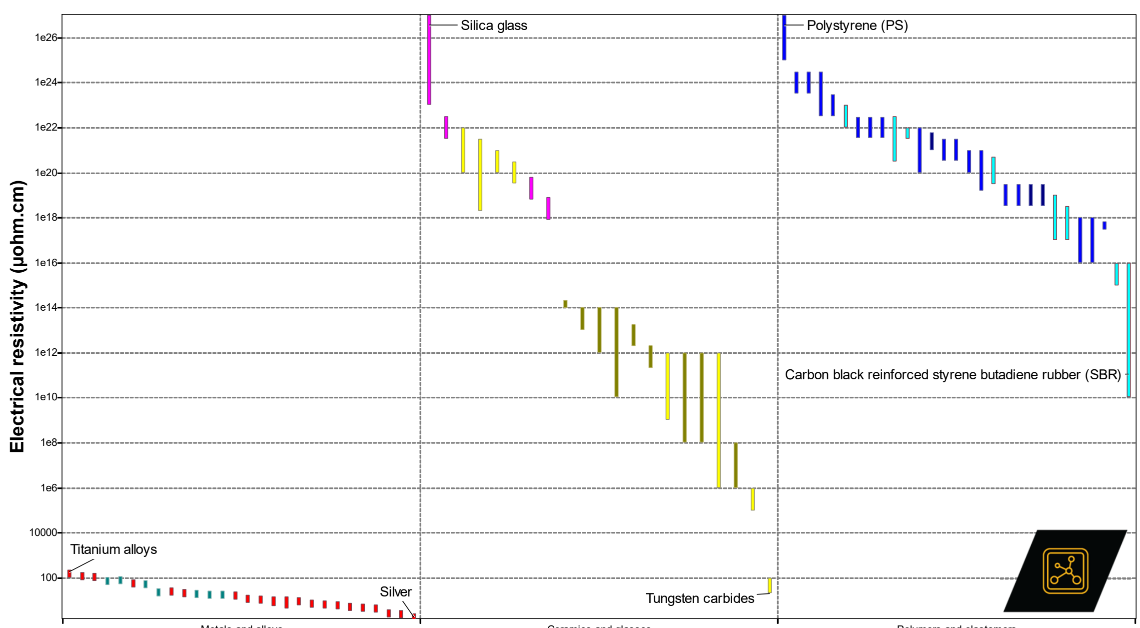


Relationship between properties - elements

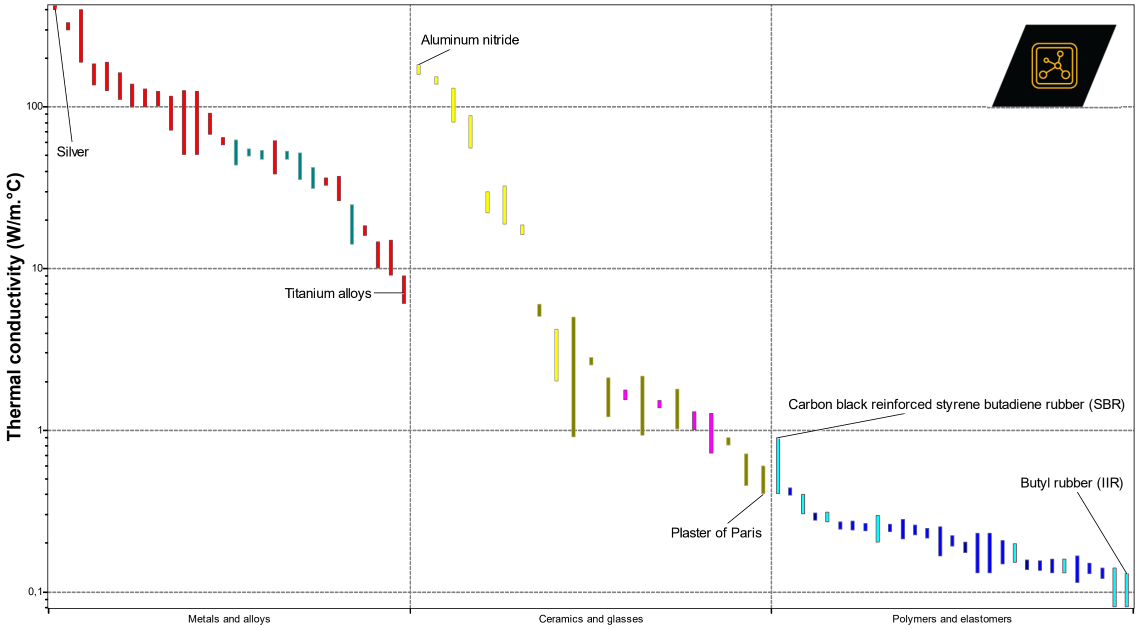




Materials properties
Electrical resistivity



Materials properties
Thermal conductivity

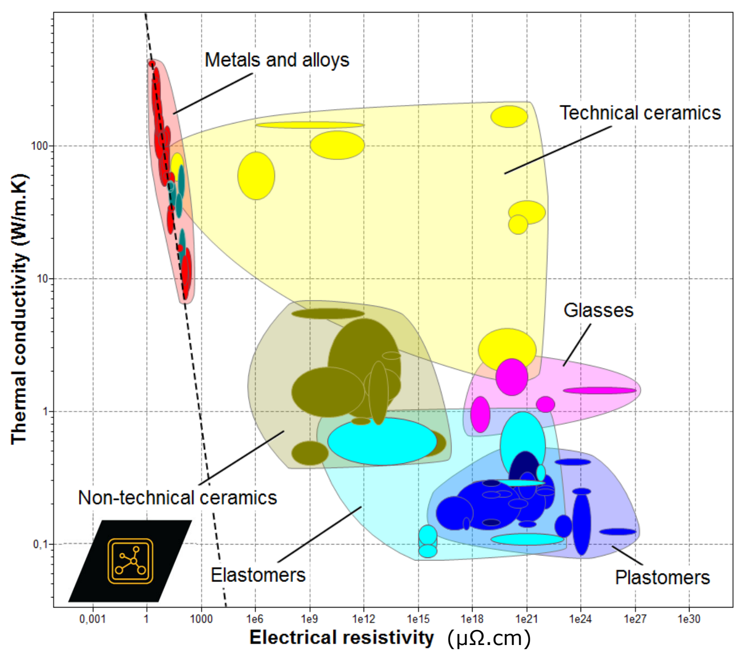


Materials property chart (level 2)

- Thermal conductivity

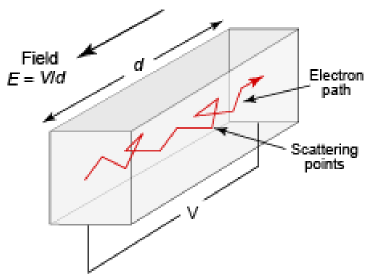
  vs.

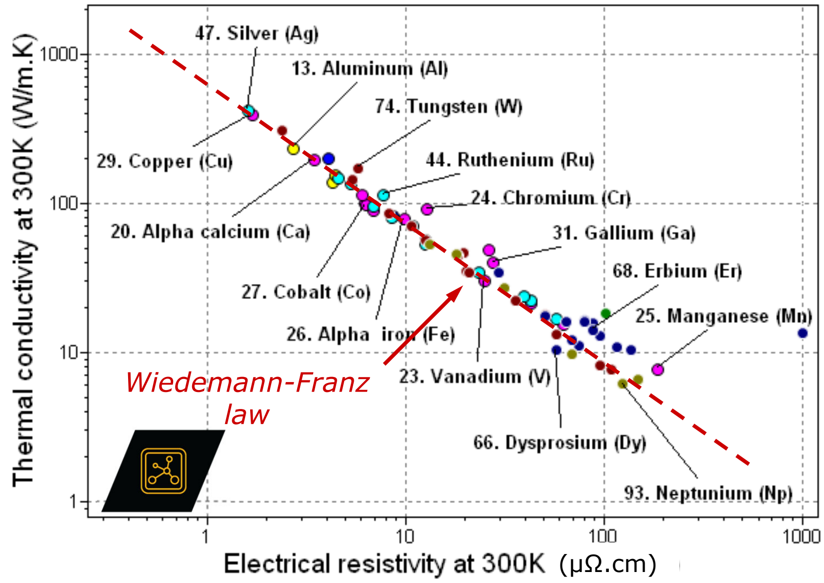
  electrical resistivity



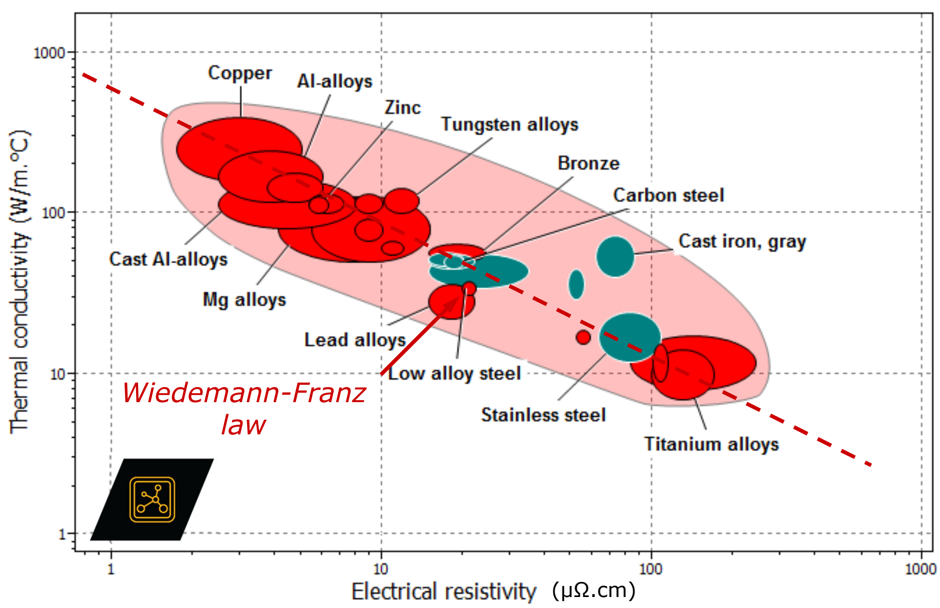
Relationship between properties - elements

Electrical and thermal conduction





Relationship between properties - materials



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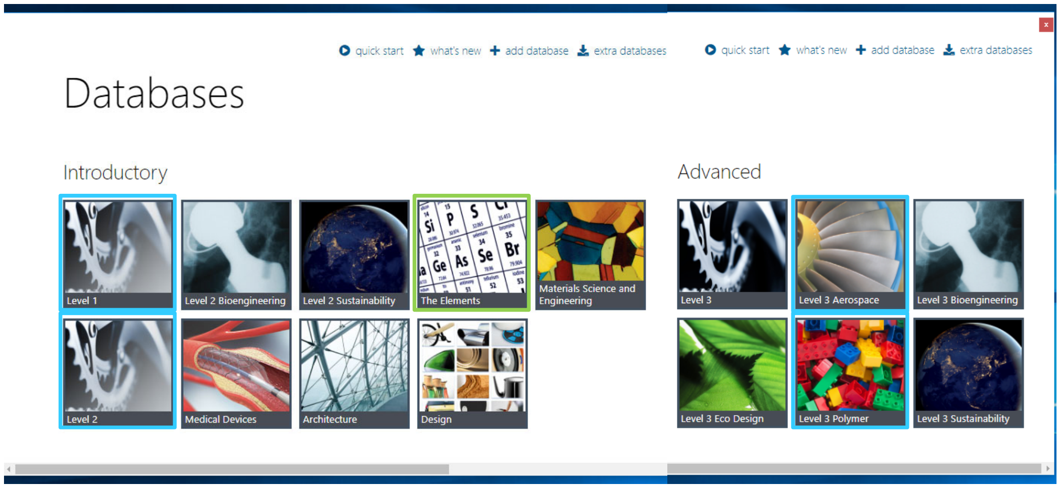
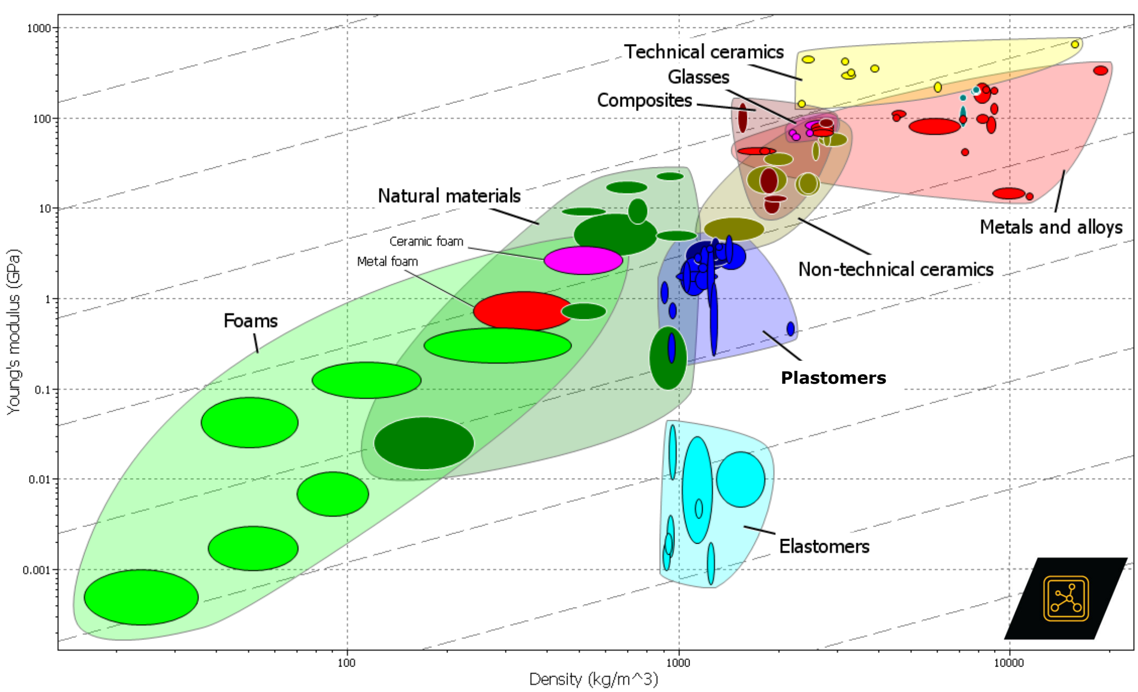
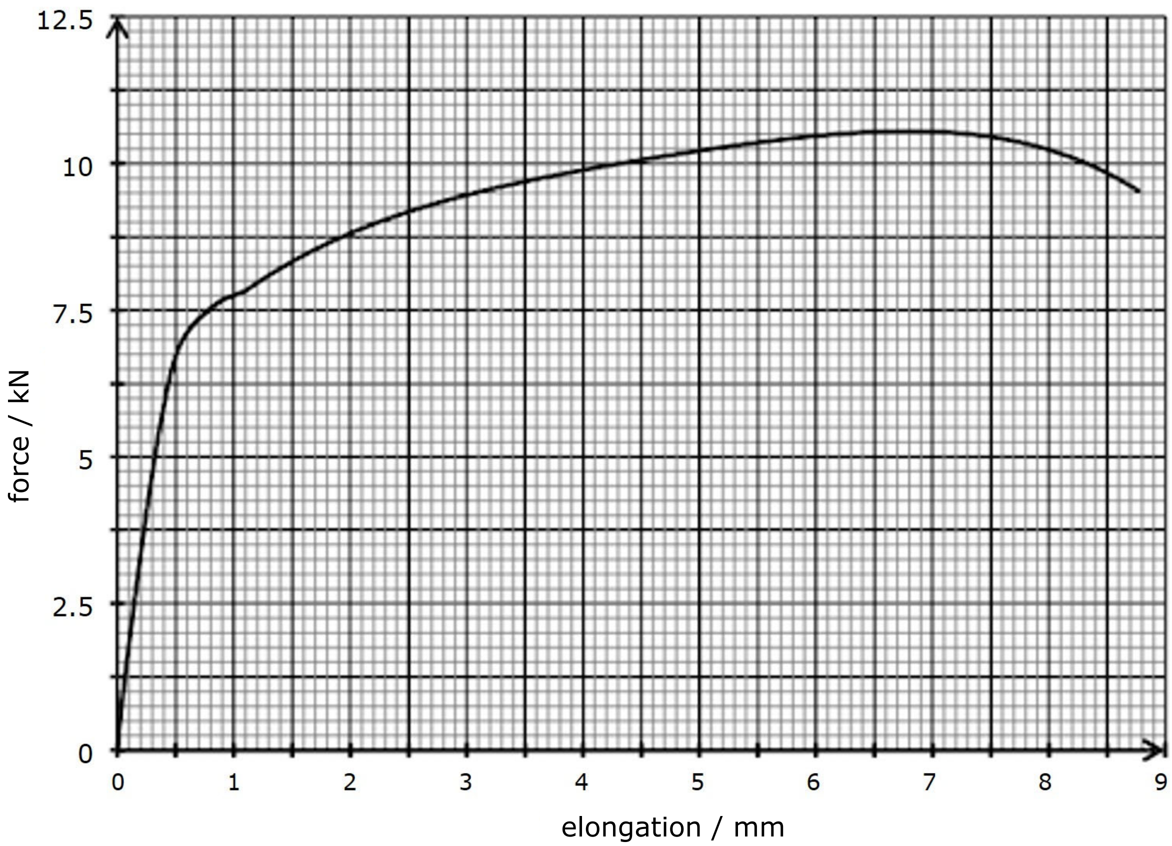
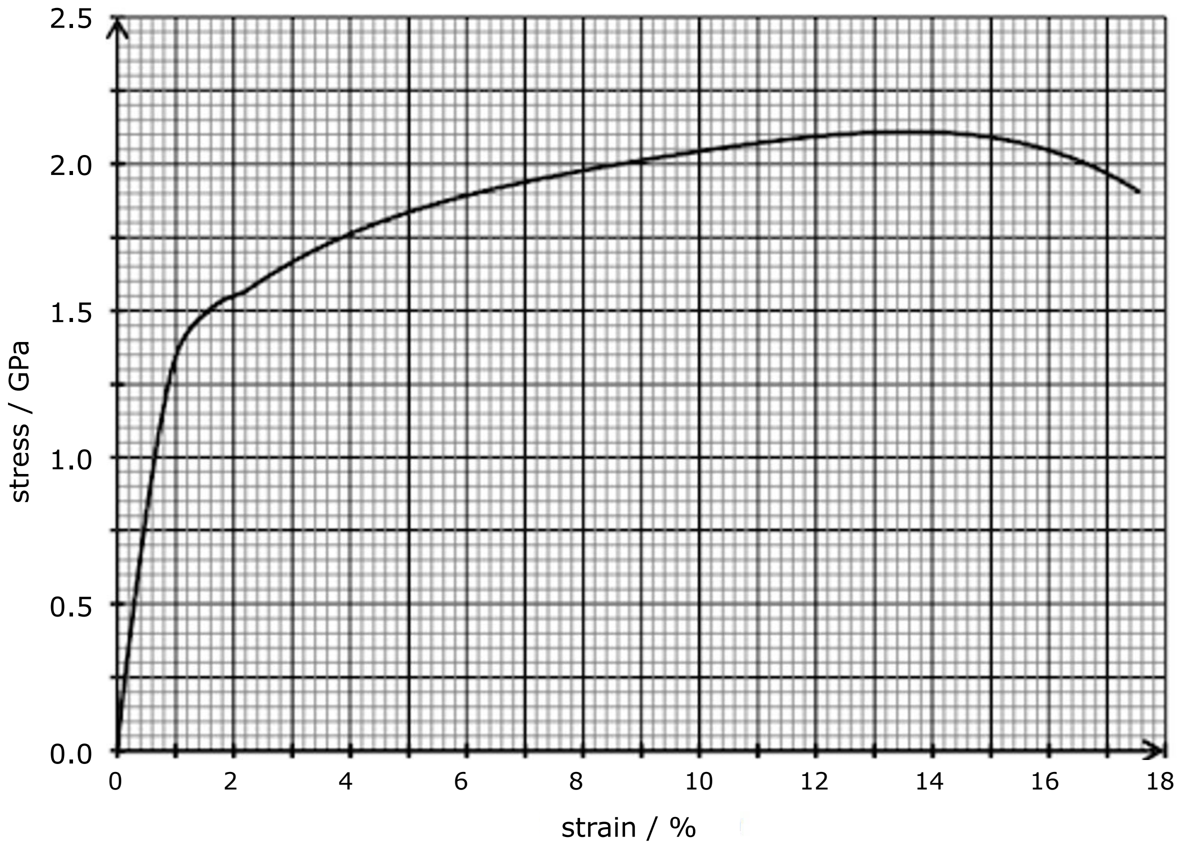


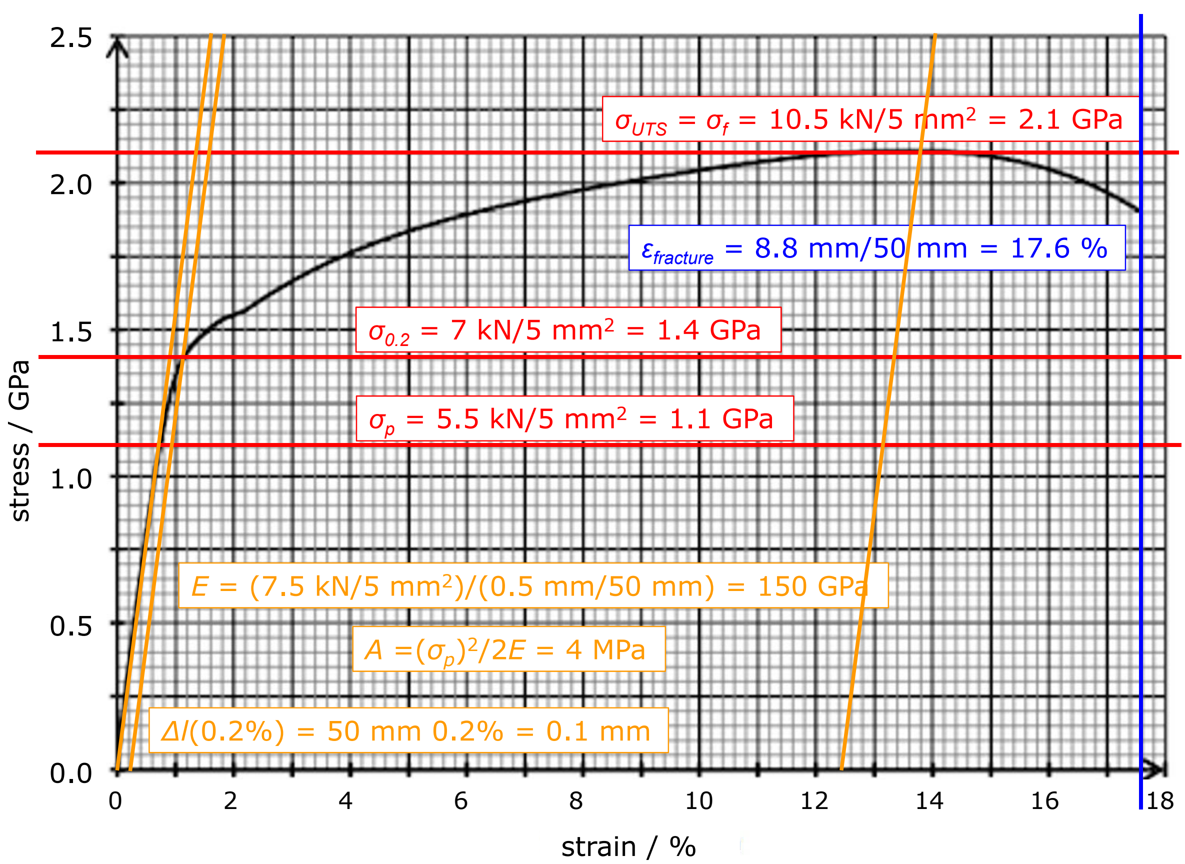
Materials property chart (level 2) Young's modulus vs. mass density



Group exercises




2.5
2.0
1.5
1.0
0.5
0.0
stress / GPa
0
2
4
6
8
10
12
14
16
18
strain / %


σ_{UTS} = σ_f = 10.5 kN/5 mm² = 2.1 GPa
$\varepsilon_{fracture}$ = 8.8 mm/50 mm = 17.6 %
$\sigma_{0.2}$ = 7 kN/5 mm² = 1.4 GPa
σ_p = 5.5 kN/5 mm² = 1.1 GPa
E = (7.5 kN/5 mm²)/(0.5 mm/50 mm) = 150 GPa
A =(σ_p)²/2E = 4 MPa
Δl(0.2%) = 50 mm 0.2% = 0.1 mm
2.5
2.0
1.5
1.0
0.5
0.0
stress / GPa
0
2
4
6
8
10
12
14
16
18
strain / %

Stiff and lightweight rod

$$\sigma = \frac{F}{A_0} \qquad \varepsilon = \frac{\Delta l}{l_0} \qquad \sigma = E\varepsilon$$

$$A_0 = \frac{Fl_0}{E\Delta l} \qquad d_0 = \sqrt{\frac{4A_0}{\pi}} = \sqrt{\frac{4}{\pi}\frac{Fl_0}{E\Delta l}} = \sqrt{\frac{4}{\pi}\frac{mgl_0}{E\Delta l}}$$

	Fe	W	Ni	Al	Mg	Ti
d_0/mm	10.9	7.8	11.0	18.9	23.5	15.3
$\rho/\text{g cm}^{-3}$	7.9	19.3	8.9	2.7	1.73	4.5
m_0/kg	1.48	1.86	1.68	1.51	1.51	1.65

$$m_0 = \rho V_0 = \rho A_0 l_0 = \rho \frac{Fl_0}{E\Delta l} l_0 = \frac{\rho}{E}\frac{F}{\Delta l} l_0^2$$