Materials Selection in Mechanical Design

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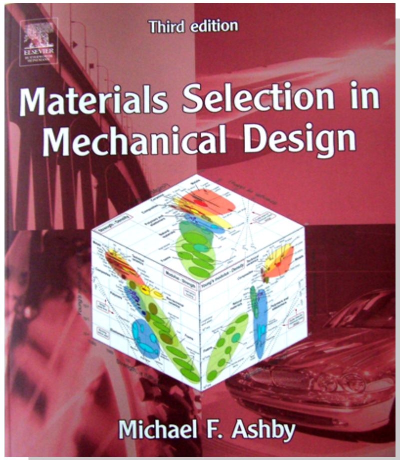
Literature

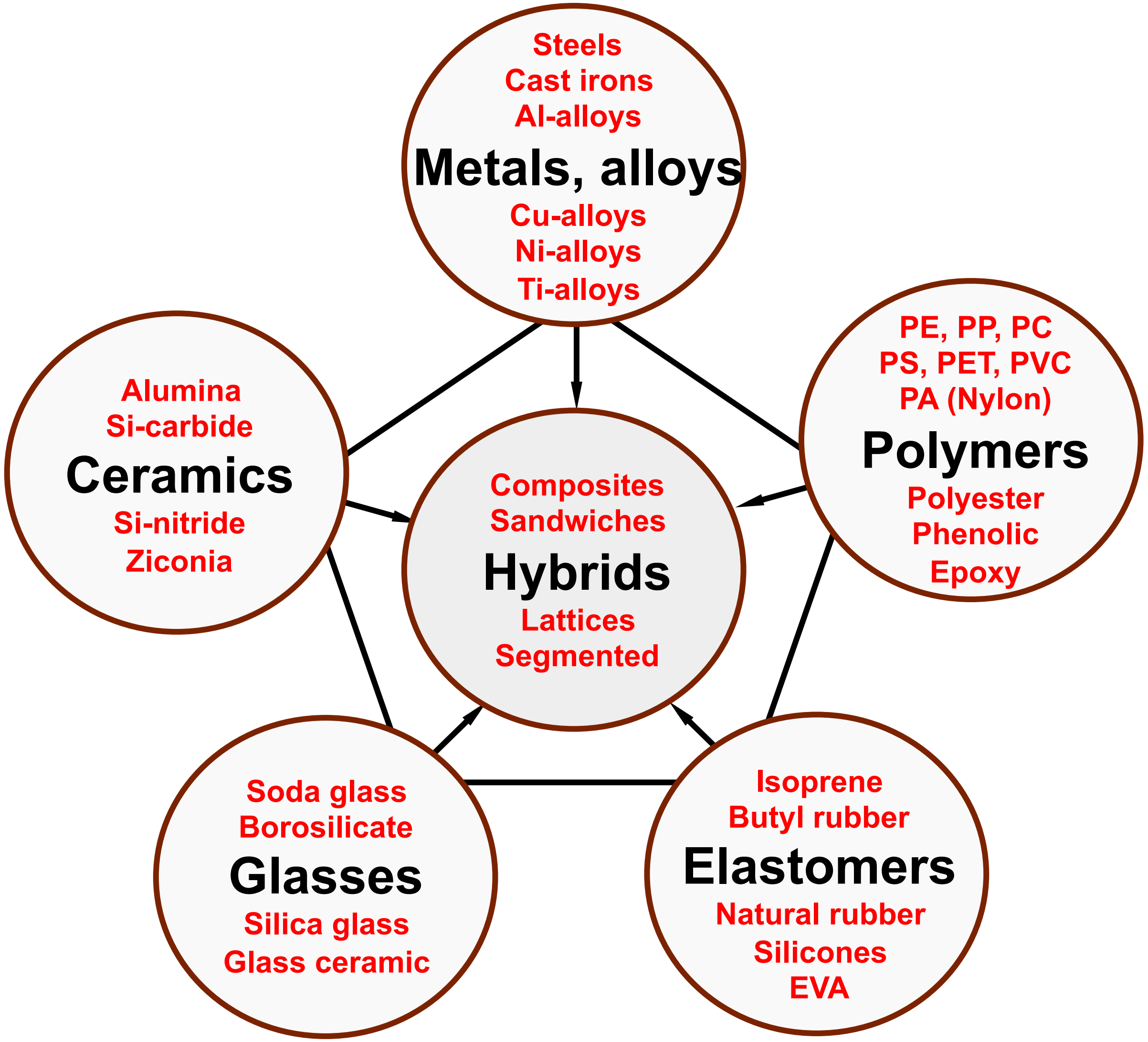


- M.F. Ashby, Materials Selection in Mechanical Design, Elsevier, Amsterdam, 2005.
- N.A. Waterman, M.F. Ashby, Materials selector, Elsevier, 1996

Epictetus, AD 50-100

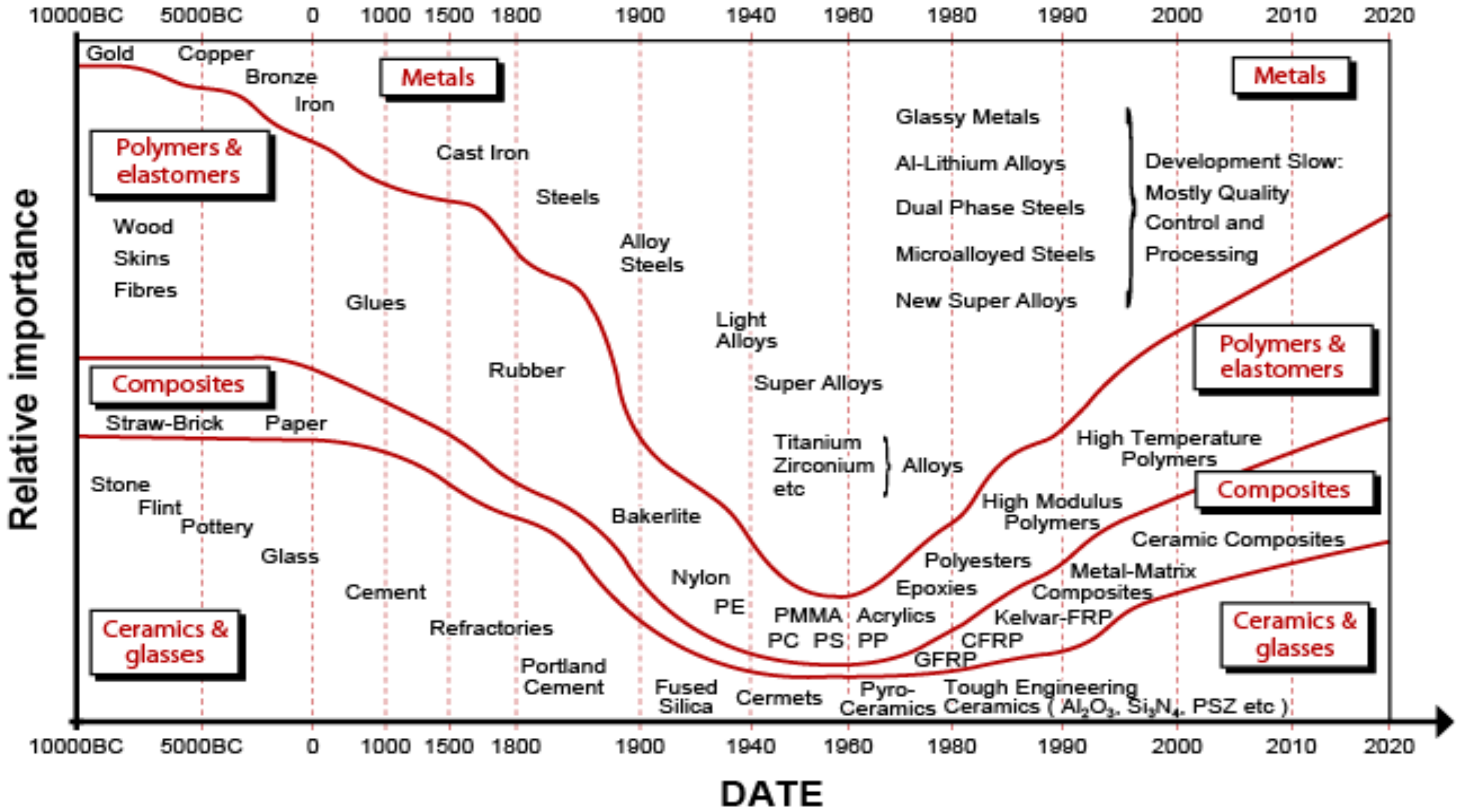
Materials of themselves, affect us little; it is the way we use them which influences our lives.

New materials very often generate new products!



Source: M.F. Ashby

Relative importance



Source: M.F. Ashby

Definitions of material properties

General:

- Density, ρ in kg/m^3
- Price, C_m in €/kg

Definitions of material properties

Mechanical:

- Elastic moduli, E, G in GPa
- Yield strength, σ_y in MPa
- Ultimate strength, σ_u in MPa
- Compressive strength, σ_c in MPa
- Failure strength, σ_f in MPa
- Hardness, H in Vickers, Brinell, …
- Elongation, ε in -

Definitions of material properties

Mechanical (continued):

- Fatigue endurance limit, σ_e in MPa
- Fracture toughness, K_{IC} in MPa*$m^{1/2}$
- Toughness, G_{IC} in kJ/m^2
- Loss coefficient (damping), η in -

Definitions of material properties

Thermal:

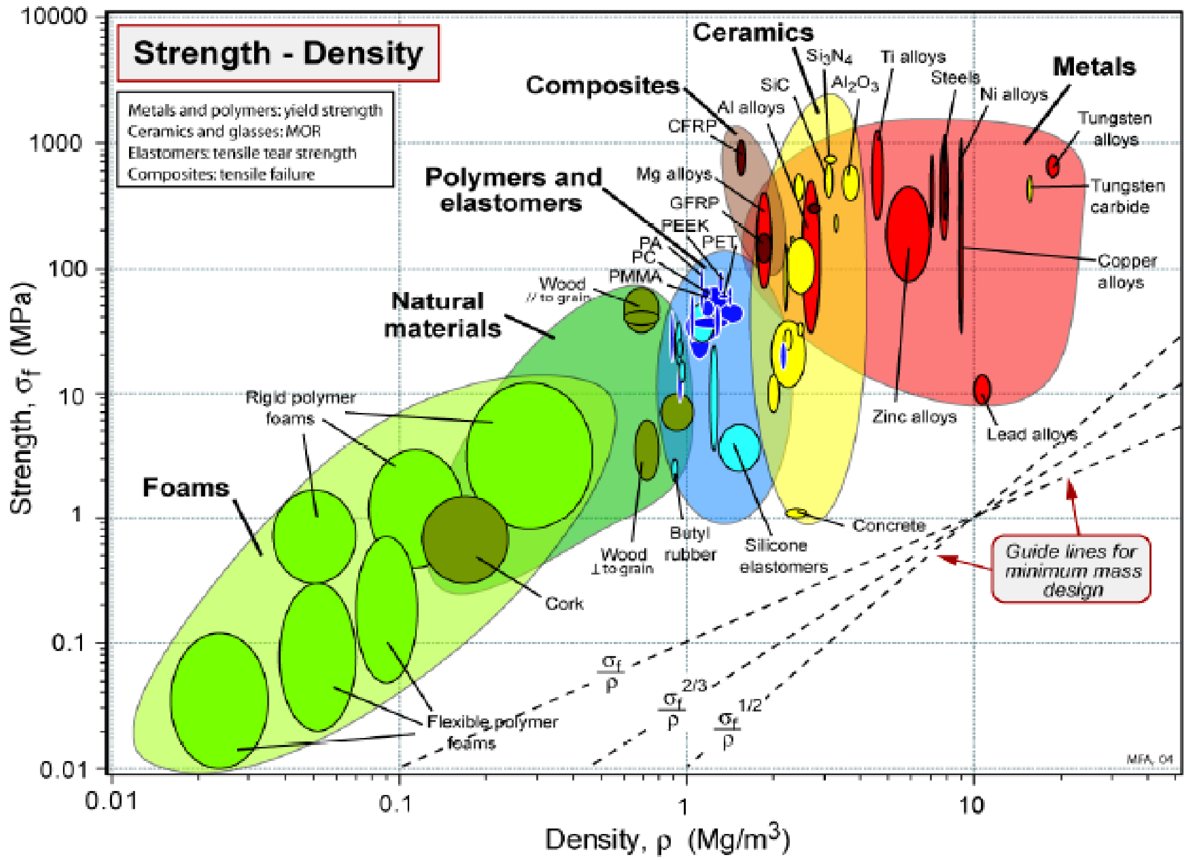
- Melting point, T_m in K
- Maximum service temperature, T_{max} in K
- Minimum service temperature, T_{min} in K
- Thermal conductivity, λ in W/m.K
- Specific heat, C_p in J/kg.K
- Thermal expansion, α in K^{-1}
- Glass temperature, T_g in K
- Thermal shock resistance, ΔT_s in K

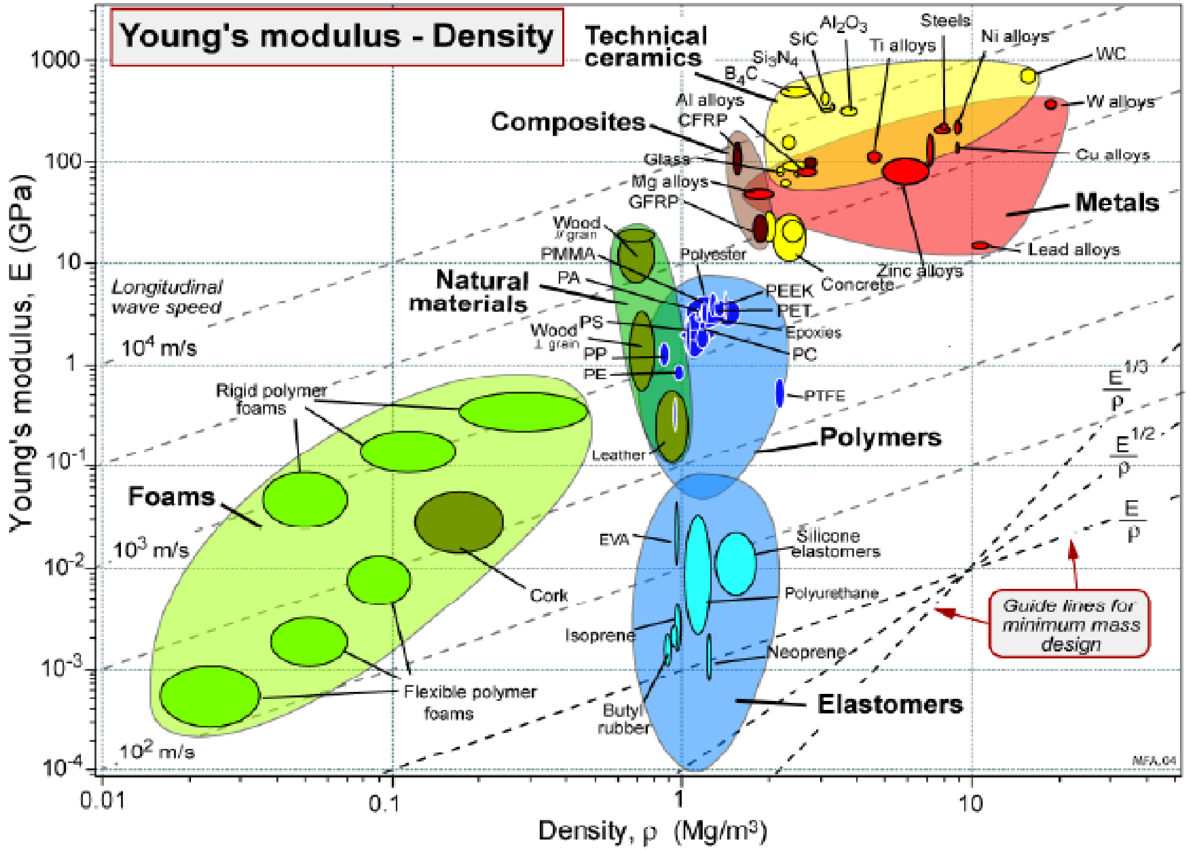
Definitions of material properties

- Electrical
  - Electrical resistivity, ρ_e in Ω.m
  - Dielectric constant, ε_d in –
  - Breakdown potential, V_b in V/m
  - Power factor, P in -
- Optical
  - Optical, transparent, translucent, opaque
  - Refractive index, η in -

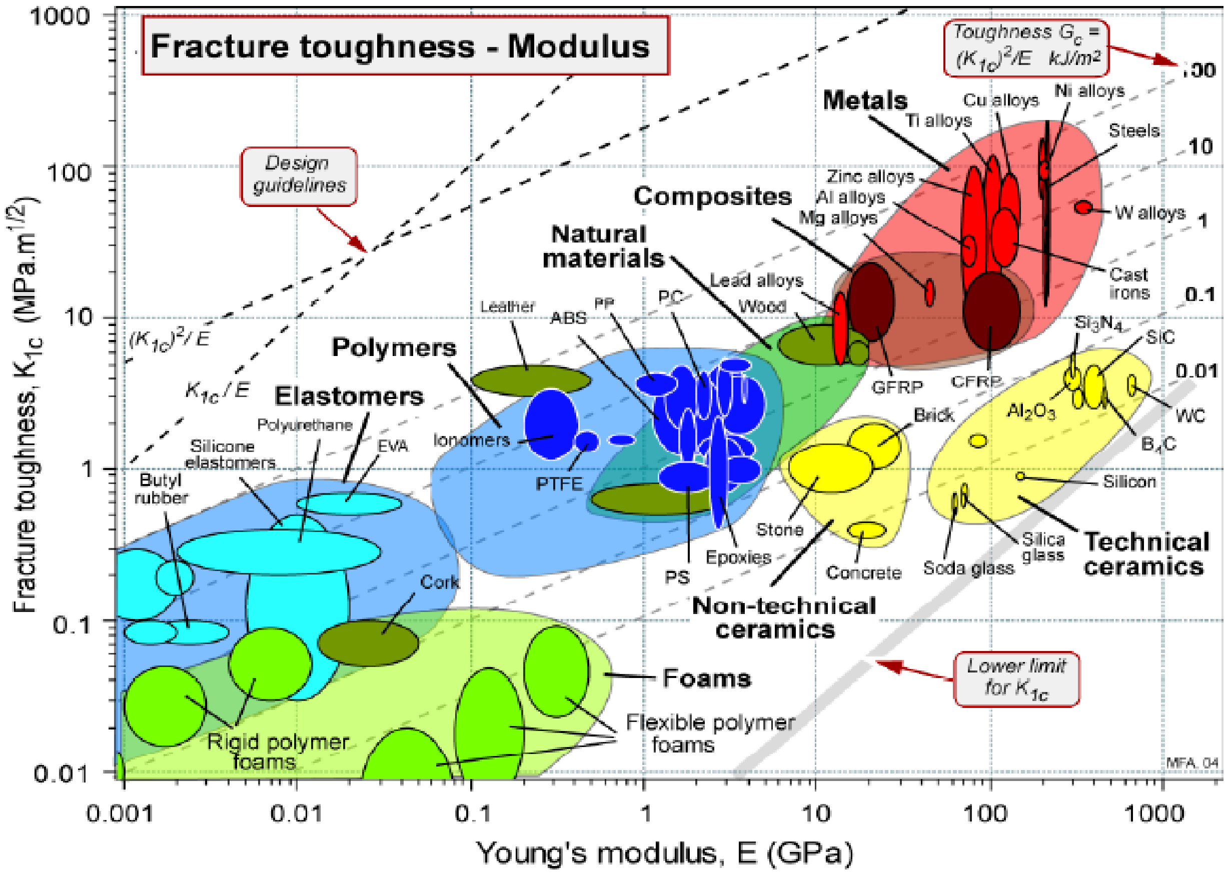
Definitions of material properties

- Eco-properties
  - Energy/kg to extract material , E_f in KJ/kg
  - CO_2/kg to extract material, CO_2 in Kg/Kg
- Environmental resistance
  - Oxidation rates
  - Corrosion rates
  - Wear rate

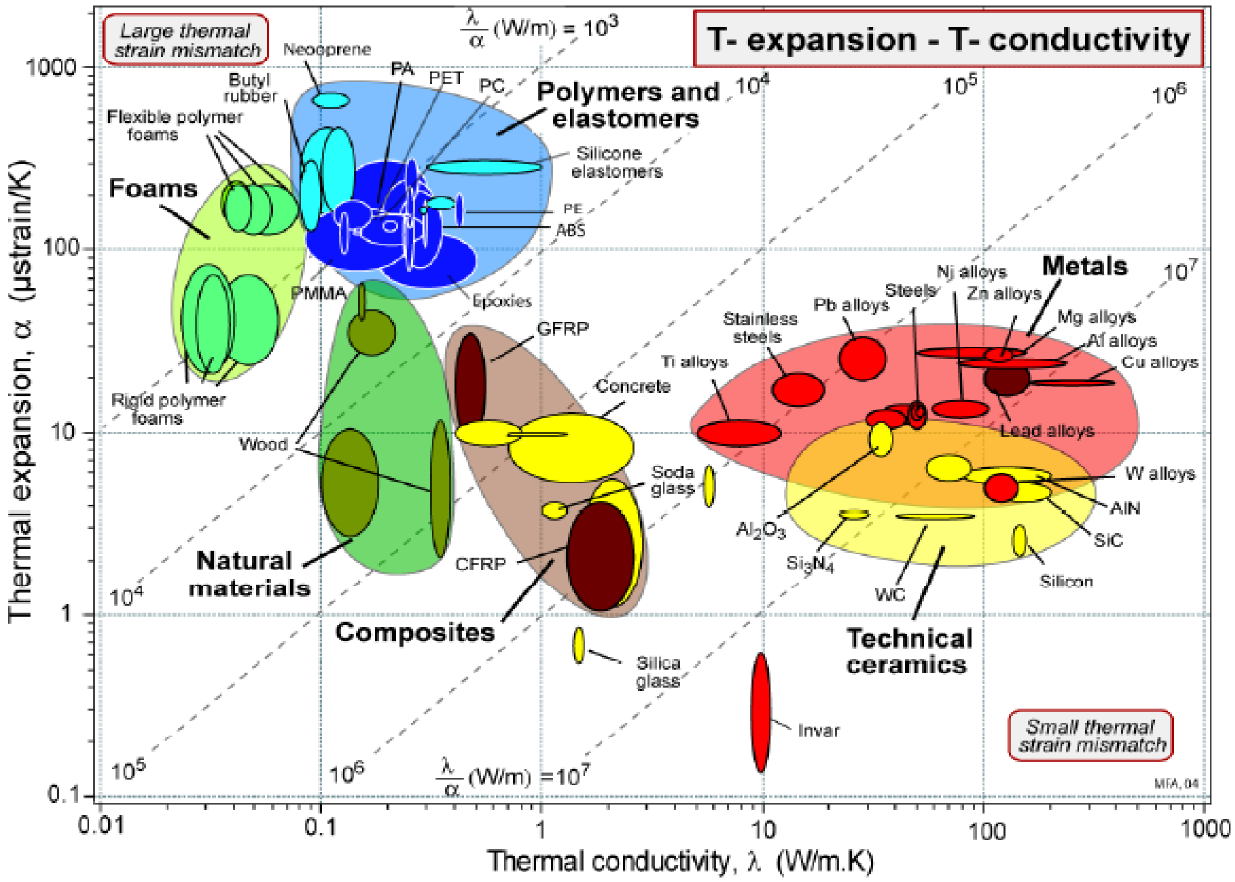

Strength - Density
Metals and polymers: yield strength
Ceramics and glasses: MOR
Elastomers: tensile tear strength
Composites: tensile failure
Ceramics
Composites
Metals
Polymers and elastomers
Natural materials
Foams
Rigid polymer foams
Flexible polymer foams
Cork
Wood ⊥ to grain
Wood // to grain
Butyl rubber
Silicone elastomers
Concrete
Zinc alloys
Lead alloys
Copper alloys
Tungsten carbide
Tungsten alloys
Ni alloys
Steels
Ti alloys
Al_2O_3
Si_3N_4
SiC
Al alloys
CFRP
Mg alloys
GFRP
PEEK
PET
PA
PC
PMMA
Guide lines for minimum mass design
$\frac{\sigma_f}{\rho}$
$\frac{\sigma_f^{2/3}}{\rho}$
$\frac{\sigma_f^{1/2}}{\rho}$
Strength, σ_f (MPa)
Density, ρ (Mg/m^3)
10000
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
MFA, 04

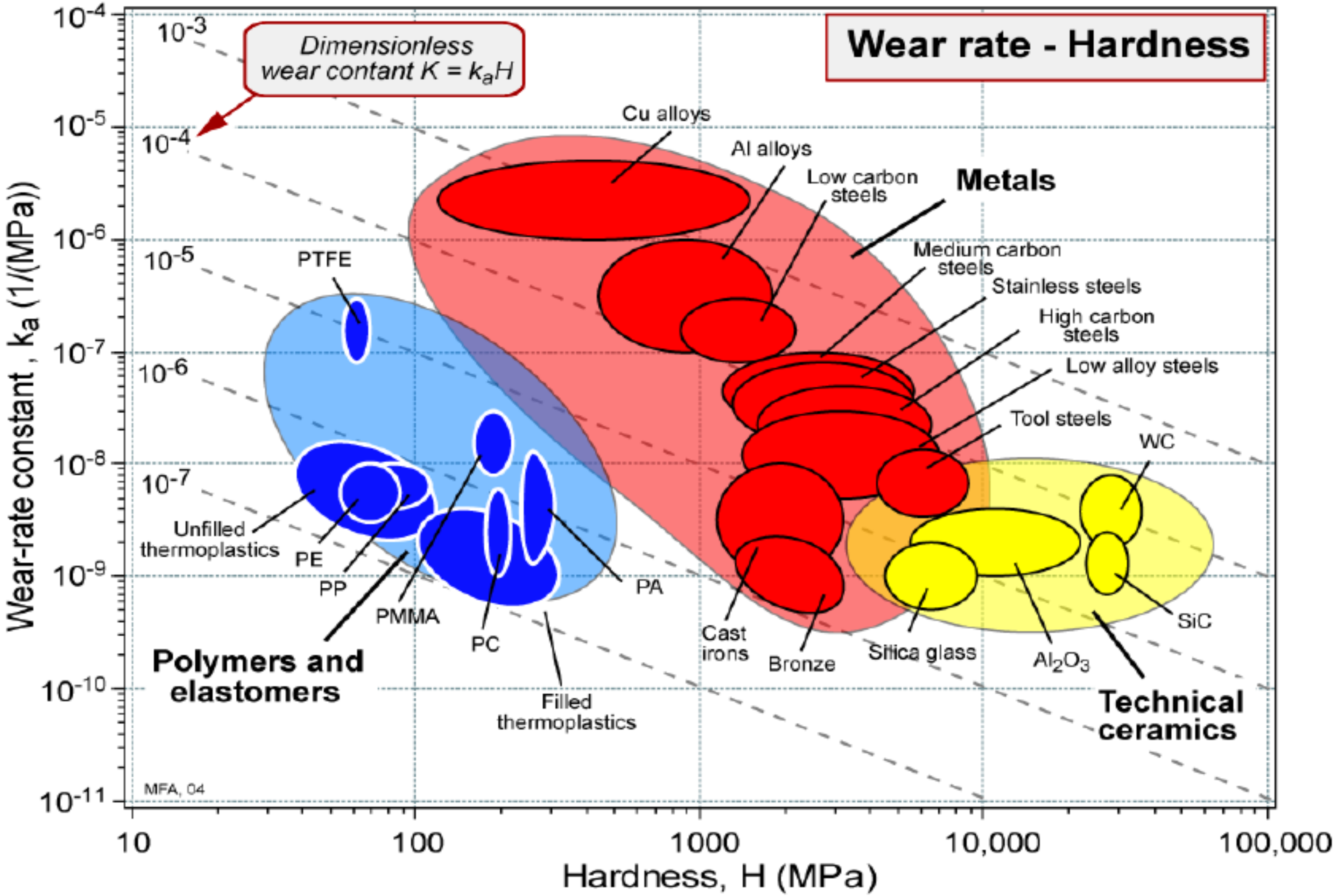


Young's modulus - Density
Technical ceramics
Composites
Natural materials
Polymers
Metals
Foams
Elastomers
Longitudinal wave speed
10^4 m/s
10^3 m/s
10^2 m/s
Rigid polymer foams
Flexible polymer foams
Cork
Leather
Wood // grain
Wood ⊥ grain
PMMA
PA
PS
PP
PE
Polyester
PEEK
PET
Epoxies
PC
PTFE
Al alloys
CFRP
Glass
Mg alloys
GFRP
B_4C
Si_3N_4
SiC
Al_2O_3
Ti alloys
Steels
Ni alloys
WC
W alloys
Cu alloys
Lead alloys
Zinc alloys
Concrete
EVA
Silicone elastomers
Polyurethane
Isoprene
Neoprene
Butyl rubber
Guide lines for minimum mass design
$\frac{E^{1/3}}{\rho}$
$\frac{E^{1/2}}{\rho}$
$\frac{E}{\rho}$
Young's modulus, E (GPa)
Density, ρ (Mg/m³)
MFA 04

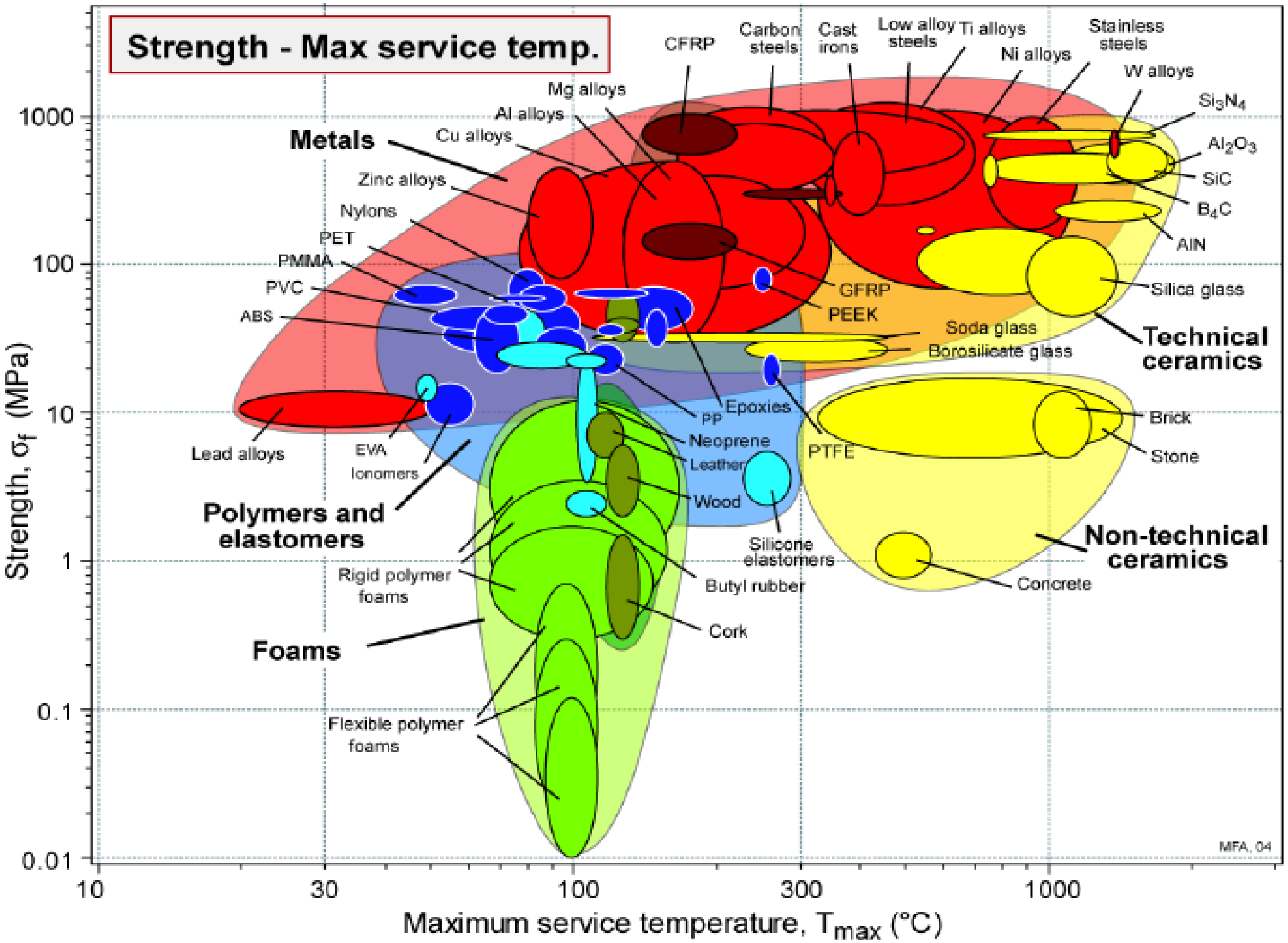


Fracture toughness - Modulus
Toughness G_c = $(K_{1c})^2/E$ kJ/m²
Design guidelines
$(K_{1c})^2/E$
K_{1c}/E
Metals
Composites
Natural materials
Polymers
Elastomers
Foams
Non-technical ceramics
Technical ceramics
Lower limit for K_{1c}
Fracture toughness, K_{1c} (MPa.m$^{1/2}$)
Young's modulus, E (GPa)

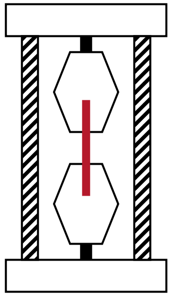

T- expansion - T- conductivity
Large thermal strain mismatch
Small thermal strain mismatch
λ/α (W/m) = 10^3
10^4
10^5
10^6
10^7
λ/α (W/m) =10^7
Neoprene
Butyl rubber
Flexible polymer foams
PA
PET
PC
Polymers and elastomers
Silicone elastomers
PE
ABS
Foams
PMMA
Epoxies
Rigid polymer foams
Wood
GFRP
Concrete
Soda glass
CFRP
Natural materials
Composites
Silica glass
Invar
Stainless steels
Ti alloys
Pb alloys
Steels
Ni alloys
Zn alloys
Metals
Mg alloys
Al alloys
Cu alloys
Lead alloys
W alloys
AlN
SiC
Silicon
Al2O3
Si3N4
WC
Technical ceramics
Thermal expansion, α (μstrain/K)
Thermal conductivity, λ (W/m.K)
MFA, 04

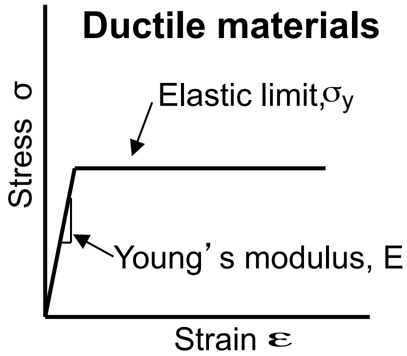


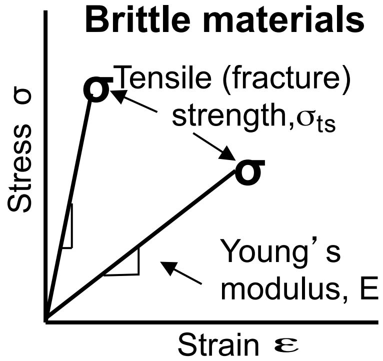
Wear rate - Hardness
Dimensionless wear contant K = k_a H
10^-3
10^-4
10^-5
10^-6
10^-7
Wear-rate constant , k_a (1/(MPa))
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
Hardness, H (MPa)
10
100
1000
10,000
100,000
Cu alloys
Al alloys
Low carbon steels
Metals
Medium carbon steels
Stainless steels
High carbon steels
Low alloy steels
Tool steels
WC
PTFE
Unfilled thermoplastics
PE
PP
PMMA
PC
PA
Polymers and elastomers
Filled thermoplastics
Cast irons
Bronze
Silica glass
Al2O3
SiC
Technical ceramics
MFA, 04


Strength - Max service temp.
Metals
Polymers and elastomers
Foams
Technical ceramics
Non-technical ceramics
CFRP
Carbon steels
Cast irons
Low alloy steels
Ti alloys
Ni alloys
Stainless steels
W alloys
Mg alloys
Al alloys
Cu alloys
Zinc alloys
Nylons
PET
PMMA
PVC
ABS
Lead alloys
EVA
Ionomers
PP
Epoxies
Neoprene
Leather
Wood
Silicone elastomers
Butyl rubber
Cork
Rigid polymer foams
Flexible polymer foams
GFRP
PEEK
PTFE
Soda glass
Borosilicate glass
Silica glass
AlN
B_4C
SiC
Al_2O_3
Si_3N_4
Brick
Stone
Concrete
MFA, 04
Strength, σ_f (MPa)
0.01
0.1
1
10
100
1000
10
30
100
300
1000
Maximum service temperature, T_{max} (°C)

Mechanical properties







General

Weight: Density ρ, Mg/m^3

Expense: Cost/kg C_m, \$/kg

Mechanical

Stiffness: Young's modulus E, GPa

Strength: Elastic limit σ_y, MPa

Fracture strength: Tensile strength σ_{ts}, MPa

Brittleness: Fracture toughness K_{ic}, $MPa.m^{1/2}$

Thermal

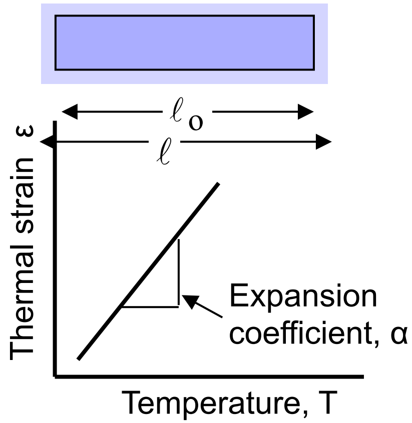
Expansion: Expansion coeff. α, 1/K

Conduction: Thermal conductivity λ, W/m.K

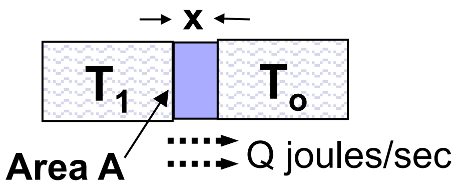
Electrical

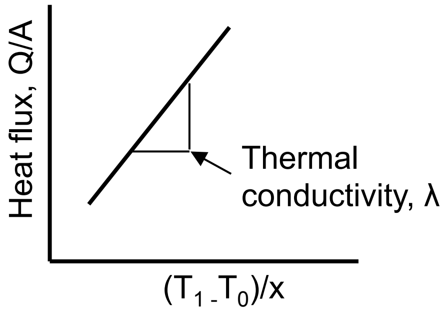
Conductor? Insulator?

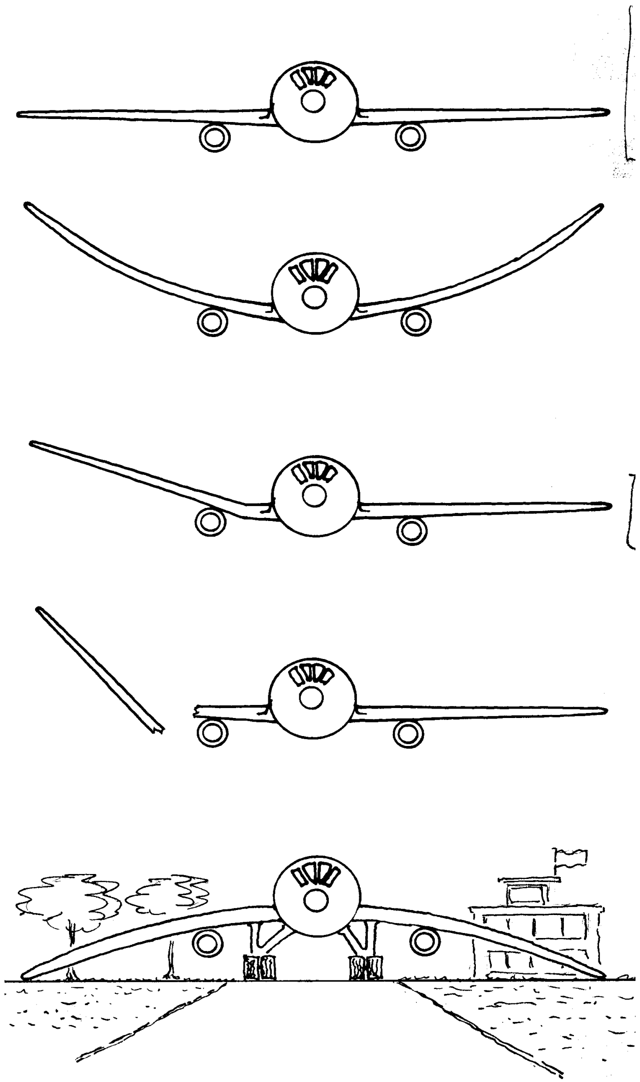
Thermal expansion



Thermal conduction







Stiff
Strong
Tough
Light

All OK !

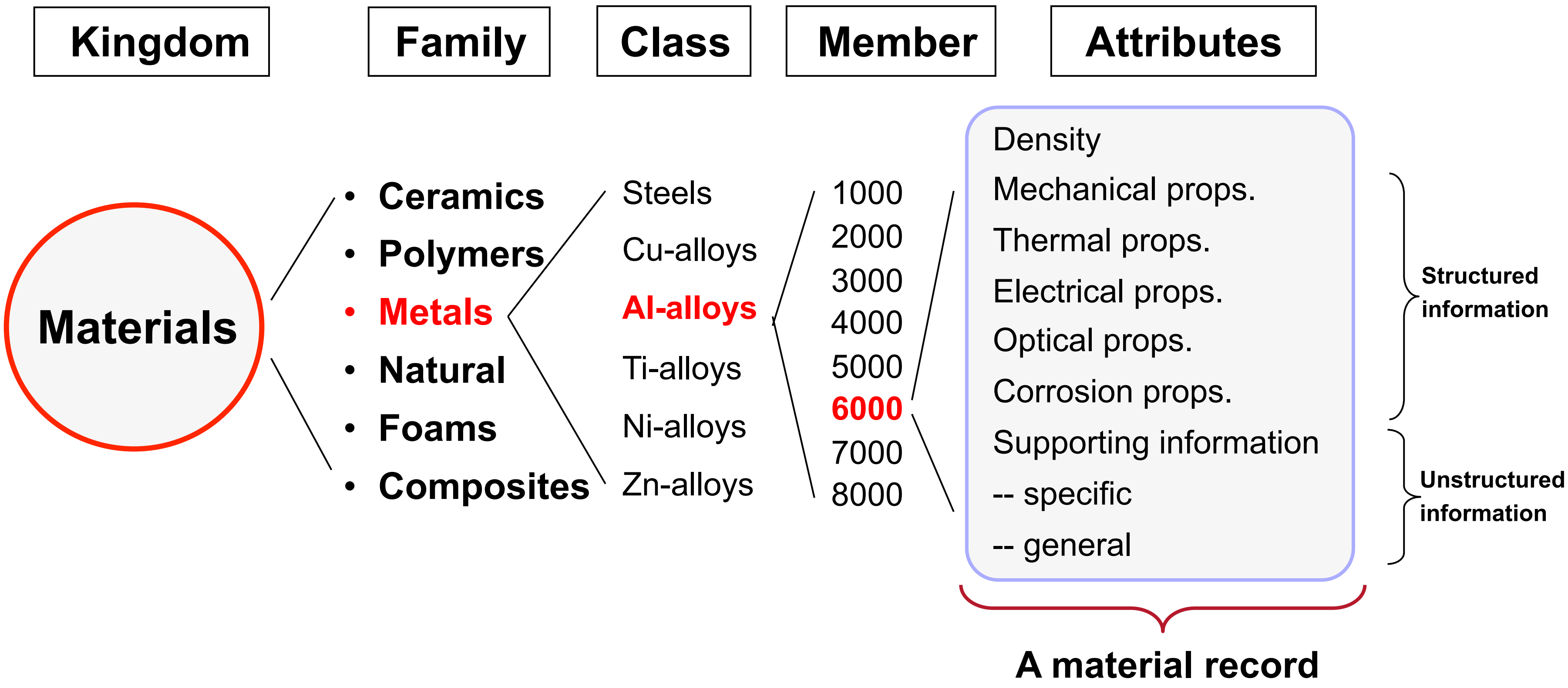
← **Not stiff enough (needs bigger E)**

← **Not strong enough (needs bigger σ_y)**

← **Not tough enough (needs bigger K_{ic})**

← **Too heavy (needs lower ρ)**

Material attributes



Structured data for ABS

Acrylonitrile-butadiene-styrene (ABS) - $(CH2\text{-}CH\text{-}C6H4)_n$

General Properties

Density	1.05 -1.07	Mg/m^3
Price	2.1 - 2.3	US $/kg

Mechanical Properties

Young's Modulus	1.1 - 2.9	GPa
Elastic Limit	18 – 50	MPa
Tensile Strength	27 – 55	MPa
Elongation	6 – 8	%
Hardness - Vickers	6 – 15	HV
Endurance Limit	11 – 22	MPa
Fracture Toughness	1.2 - 4.2	$MPa.m^{1/2}$

Thermal Properties

Max Service Temp	350 – 370	K
Thermal Expansion	70 - 75 10^{-6}	/K
Specific Heat	1500 - 1510	J/kg.K
Thermal Conductivity	0.17 - 0.24	W/m.K

Electrical Properties

Conductor or insulator?	Good insulator

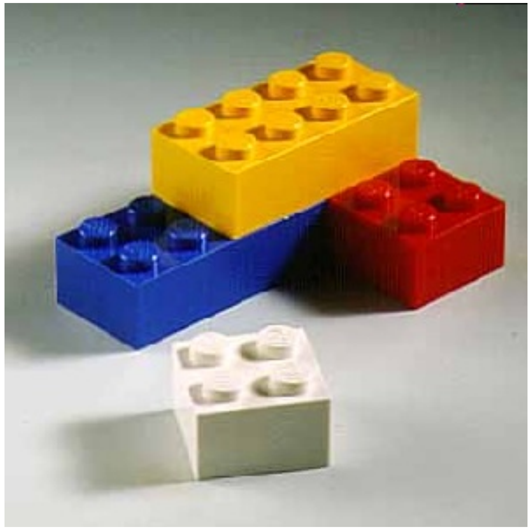
Optical Properties

Transparent or opaque?	Opaque

Corrosion and Wear Resistance

Flammability	Average
Fresh Water	Good
Organic Solvents	Average
Oxidation at 500C	Very Poor
Sea Water	Good
Strong Acid	Good
Strong Alkalis	Good
UV	Good
Wear	Poor
Weak Acid	Good
Weak Alkalis	Good

Unstructured data for ABS



What is it? ABS (Acrylonitrile-butadiene-styrene) is tough, resilient, and easily molded. It is usually opaque, although some grades can now be transparent, and it can be given vivid colors. ABS-PVC alloys are tougher than standard ABS and, in self-extinguishing grades, are used for the casings of power tools.

Design guidelines. ABS has the highest impact resistance of all polymers. It takes color well. Integral metallics are possible (as in GE Plastics' Magix.) ABS is UV resistant for outdoor application if stabilizers are added. It is hygroscopic (may need to be oven dried before thermoforming) and can be damaged by petroleum-based machining oils.

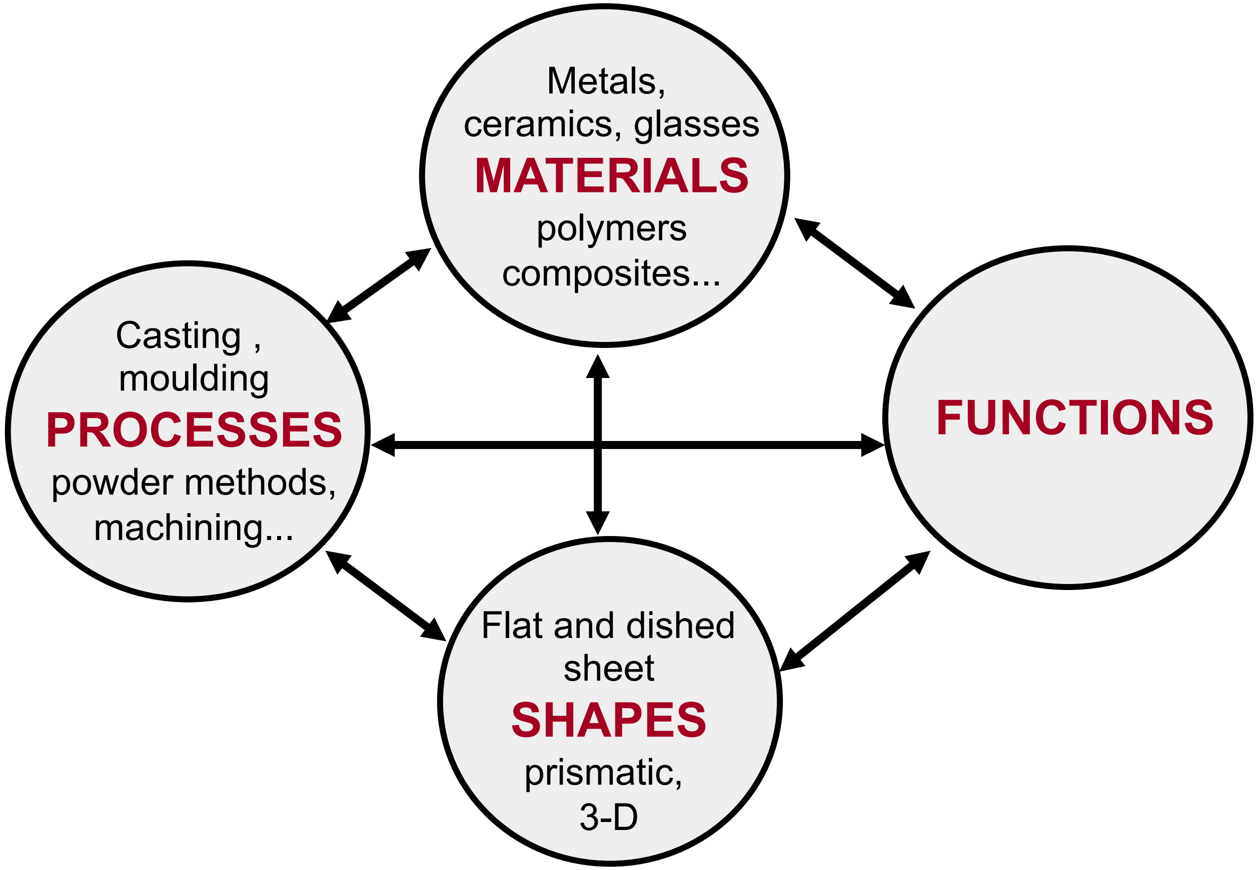
ABS can be extruded, compression moulded or formed to sheet that is then vacuum thermo-formed. It can be joined by ultrasonic or hot-plate welding, or bonded with polyester, epoxy, isocyanate or nitrile-phenolic adhesives.

Technical notes. ABS is a terpolymer - one made by copolymerising 3 monomers: acrylonitrile, butadiene and styrene. The acrylonitrile gives thermal and chemical resistance, rubber-like butadiene gives ductility and strength, the styrene gives a glossy surface, ease of machining and a lower cost. In ASA, the butadiene component (which gives poor UV resistance) is replaced by an acrylic ester. Without the addition of butyl, ABS becomes, SAN - a similar material with lower impact resistance or toughness. It is the stiffest of the thermoplastics and has excellent resistance to acids, alkalis, salts and many solvents.

Typical Uses. Safety helmets; camper tops; automotive instrument panels and other interior components; pipe fittings; home-security devices and housings for small appliances; communications equipment; business machines; plumbing hardware; automobile grilles; wheel covers; mirror housings; refrigerator liners; luggage shells; tote trays; mower shrouds; boat hulls; large components for recreational vehicles; weather seals; glass beading; refrigerator breaker strips; conduit; pipe for drain-waste-vent (DWV) systems.

The environment. The acrylonitrile monomer is nasty stuff, almost as poisonous as cyanide. Once polymerized with styrene it becomes harmless. ABS is FDA compliant, can be recycled, and can be incinerated to recover the energy it contains.

Materials selection - the basics



The selection strategy:

1.Translate design requirements:
Express as function, constraints, objectives and free variables.

2. Screen using constraints:
Eliminate materials that ***cannot*** do the job.

3. Rank using objective:
Find the screened materials that do the job ***best***.

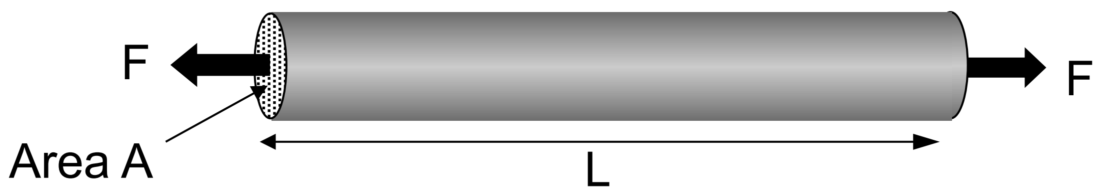
4. Seek supporting information:
Research the family history of top-ranked candidates.

Translate design requirements

- Function
  - What does the component do?
- Constraints
  - What non-negotiable conditions must be met?
  - What negotiable but desirable conditions
- Objective
  - What is to be maximized or minimized?
- Free variables
  - What parameters of the problem is the designer free to change?

Example: Strong & light tie-rod

Strong tie of length L and minimum mass



Function: *Tie-rod*

Objective: *Minimise mass m:*

$$m = A L \rho \qquad (1)$$

Constraints:

- *Length L is specified*
- *Must not fail under load F*
- *Adequate fracture toughness*

Equation for constraint on A:

$$F/A < \sigma_y \qquad (2)$$

m = mass
A = area
L = length
ρ = density
σ_y = yield strength

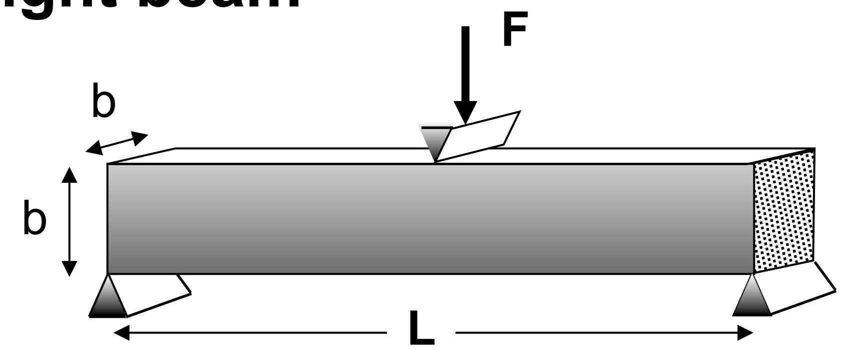
Free variables:

- *Material choice*
- *Section area A; eliminate in (1) using (2):*

$$m = FL\left(\frac{\rho}{\sigma_y}\right)$$

Chose materials with smallest $\left(\frac{\rho}{\sigma_y}\right)$

Example: Stiff & light beam



Function — *Beam* (solid square section).

Objective — *Minimise mass*, m, where:

$$m = AL\rho = b^2 L\rho$$

Constraint — *Stiffness* of the beam S:

$$S = \frac{CEI}{L^3}$$

I is the second moment of area:

$$I = \frac{b^4}{12}$$

- m = mass
- A = area
- L = length
- ρ = density
- b = edge length
- S = stiffness
- I = second moment of area
- E = Youngs Modulus

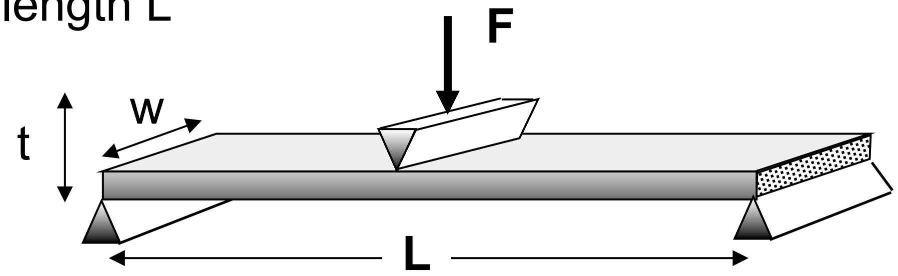
Free variables
- *Material choice.*
- *Edge length b.* Combining the equations gives:

$$m = \left(\frac{12\, S\, L^5}{C}\right)^{1/2} \left(\frac{\rho}{E^{1/2}}\right)$$

Chose materials with smallest $\left(\frac{\rho}{E^{1/2}}\right)$

Example: Stiff & light panel

Function — *Panel* with given width w and length L



Objective — *Minimise mass*, m, where

$$m = AL\rho = w\,t\,L\rho$$

Constraint — *Stiffness* of the panel S:

$$S = \frac{CEI}{L^3}$$

I is the second moment of area:

$$I = \frac{w\,t^3}{12}$$

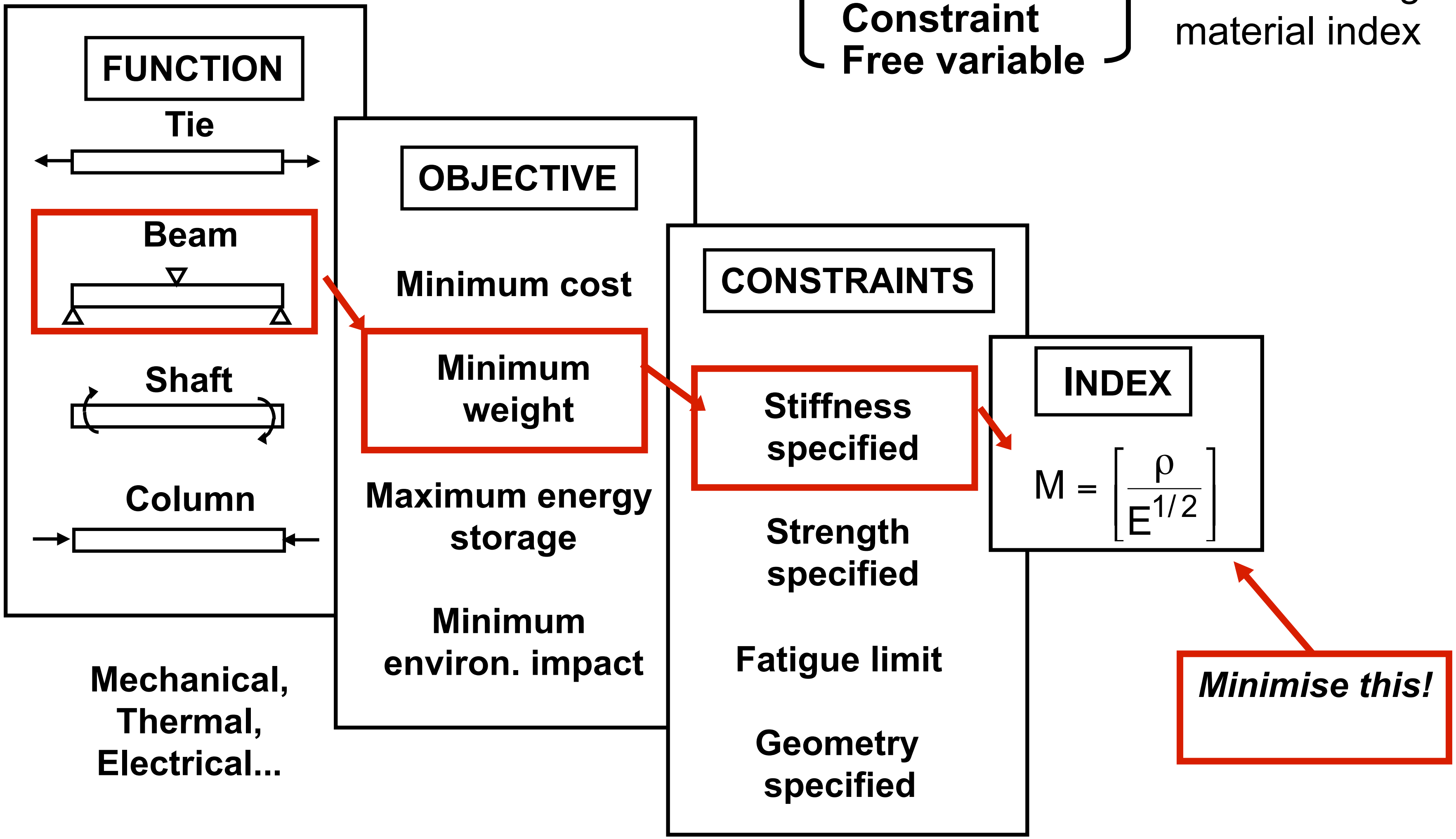
m = mass
w = width
L = length
ρ = density
t = thickness
S = stiffness
I = second moment of area
E = Youngs Modulus

Free variables
- *Material choice.*
- *Panel thickness t.* Combining the equations gives:

$$m = \left(\frac{12\,S\,w^2}{C}\right)^{1/3} L^2 \left(\frac{\rho}{E^{1/3}}\right)$$

Chose materials with smallest $\left(\frac{\rho}{E^{1/3}}\right)$

Each combination of { **Function**, **Objective**, **Constraint**, **Free variable** } Has a characterising material index

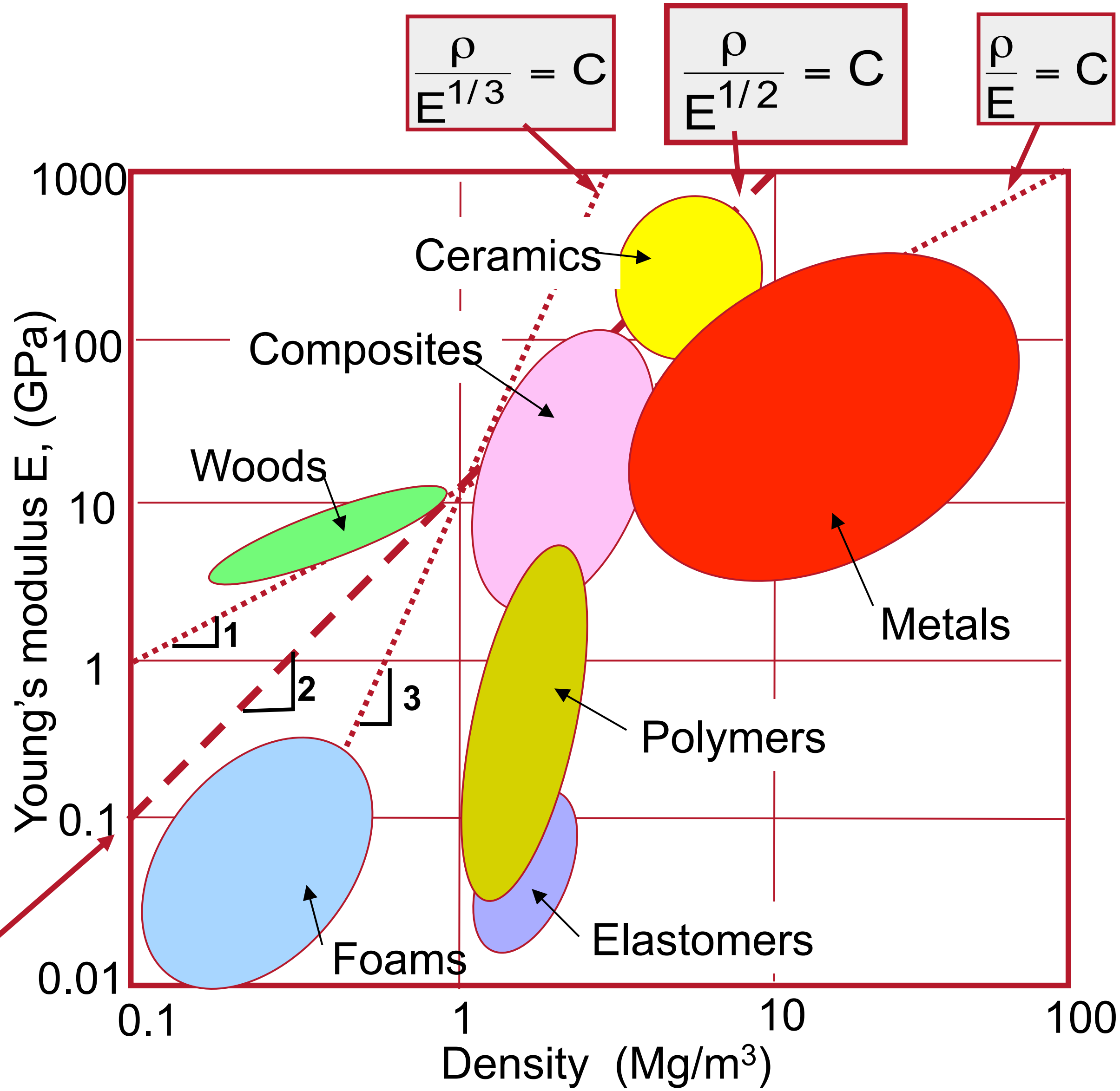


Index: $M = \frac{\rho}{E^{1/2}}$

$\Rightarrow E = \rho^2 / M^2$

$\text{Log}(E) = 2\text{Log}(\rho) - 2\text{Log}(M)$

Contours of constant M are lines of slope 2 on an E-ρ chart



Example case studies:

1. Automotive headlight lens
2. Novel guitar case
3. Design a CD case that does not crack or scratch CD's
4. Materials for knife-edge and pivots
5. Cork extractors
6. Bicycle frames

More example

7. Containers for liquid drinks
8. Electrical plugs
9. Micro wave dishes
10. A fan blade for an aircraft turbine design

Automotive headlight lens

- The lens of an automobile headlamp protects the bulb and reflector and focusses the light where it is most needed.
- Project: Select materials for the lens.
- Requirements:
  - Must be **transparent** with **optical quality**.
  - Must be able to be **molded** easily.
  - Must have very good **resistance to fresh and salt water**
  - Must have very good **resistance to UV light**
  - Good abrasion resistance, meaning a high **hardness**
  - Low **cost**

Novel guitar case

- Guitars are delicate instruments. They need a case to protect them when moved, and if they are electric, they need an amplifier and speaker and they too have to be moved and protected. The mission is to simplify this protection problem by designing a case that will hold and protect both the guitar and the amplifier plus speaker using the case itself as the speaker cabinet and amplifier case.

Requirements

- Must be tough – the rule of thumb here is that the **fracture toughness** should be greater than 15 in the usual units (MPa.m1/2).
- Must be **moldable**
- Very good **resistance to fresh and salt water**
- Must be **light**
- Should not **cost** too much

CD case that does not crack or scratch CD's

- *Optical properties*: transparent or optically clear.
- *Fracture toughness* better than polystyrene (get data for PS from its record).
- *Young's modulus* not too different from polystyrene (to make sure the case is stiff enough)
- Able to be *injection moulded.*
- *Cost* not more than twice that of polystyrene.

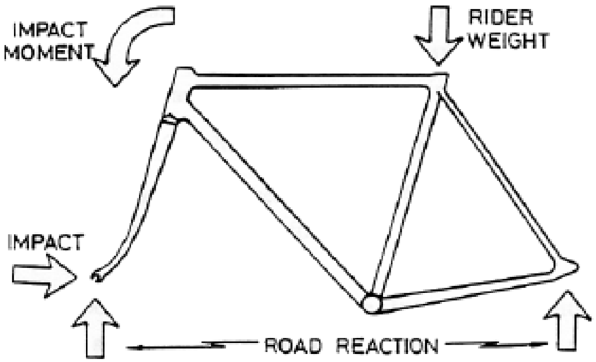
Materials for knife-edges and pivots

- Precision instruments like clocks, watches, gyroscopes, and scientific equipment often contain moving parts located by knife-edges or pivots.
- The accuracy of location is limited by the deformation of the knife-edge or pivot and the mating surface.
  - Elastic deformation is minimised by choosing materials with high Young's modulus;
  - plastic deformation is limited by choosing materials with high hardness.

Requirements

- *Young's modulus*: as large as possible.
- *Hardness:* as large as possible.

Bicycle frames



- The forks and cranks of a bike carry bending moments. The spokes and brake cables carry tension. The tubular frame of a bike carries bending, torsion and axial loads – the bending moments are usually the most severe.
- The design-load must take account of impact – riding the bike off a curb, for instance – when decelerations of 10G are possible. A lower limit of 15 MPa.m1/2 on fracture toughness is essential.
- A mountain bike is strength-limited, but stiffness is important too – a bike that is too stiff gives a harsh ride. In bikes for sprint events stiffness can be the most important consideration – excessive flexing of the frame dissipates energy.
- Stiffness and strength are constraints, not objectives (they must meet specified values). Objectives, usually, are mass and cost (for these a minimum is sought).

Design requirements for the forks of a cheap street bike

- **Function**
  - Bicycle forks – a hollow tube loaded in compression.
- **Constraints**
  - Strength specified
  - Fracture toughness > 15 MPa.m1/2.
- **Objective**
  - Minimize cost.
- **Free variables**
  - Tube wall thickness
  - Choice of material.

Appropriate material index M1

- $M1 = C_m * \rho / \sigma_y$
  - C_m = Material cost in €/Kg
  - ρ = Density in Kg/m^3
  - σ_y = Elastic limit strength in MPa
- Minimize M1
  - Steel

Design requirements for the forks of a high-performance mountain bike

- **Function**
  - Forks – a hollow tube loaded in compression.
- **Constraints**
  - Strength specified
  - Fracture toughness > 15 MPa.m1/2.
- **Objective**
  - Minimize mass
- **Free variables**
  - Tube wall thickness
  - Choice of material.

Appropriate material index M2

- $M2 = \rho / \sigma_y$
  - ρ = Density in Kg/m^3
  - σ_y = Elastic limit strength in MPa
- Minimize M2
  - Best:
    - Carbon Fiber Reinforced Composites
  - Good:
    - Titanium alloys
    - Wrought magnesium alloys

Fan blade for an aircraft turbine engine

To perform its aerodynamic function (pump air) the fan blade has to have a specified size and shape. The size to be considered here is 460 mm long x 150 mm wide by a maximum thickness of 10 mm. The shape is typically a complex airfoil with twist and taper along the radial axis, and may be hollow for weight reduction. For this problem, assume the blade to be rectangular in outer cross section with internal cavities per your description. The blade is to withstand a tensile stress σ caused by centrifugal loading. For a given angular velocity, this stress scales with the density ρ of the material of the blade:

$$\sigma = 0.11\rho \ (\sigma \text{ in MPa}, \rho \text{ in kg / m}^3)$$