Principles of Materials Selection:

A Rational Approach to Engineering Design

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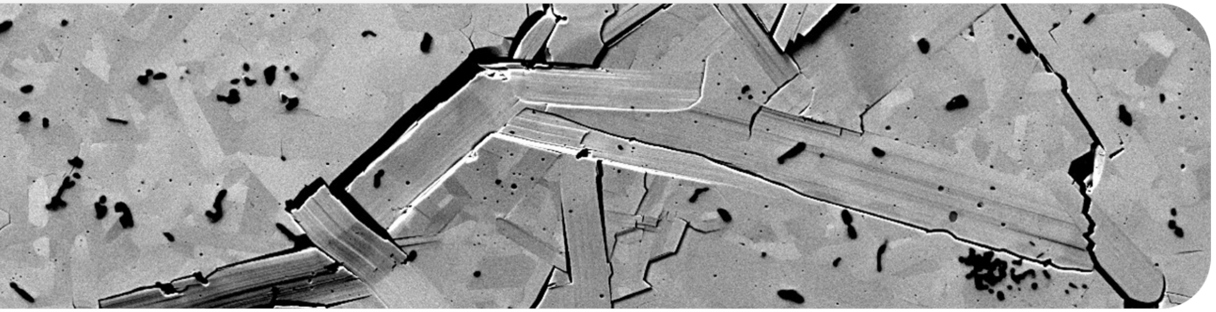


Why materials selection matters?

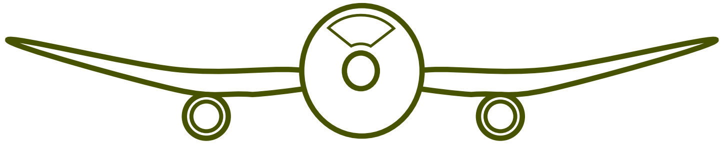
Why switch from carbon fiber to stainless steel?

SPACEX

Elon MUSK
(17/11/**2021**)

Musk, E. [@elonmusk]. (2024, June 6). If you want a detailed explanation of why I switched Starship from carbon fiber to stainless steel [Tweet]. X (formerly Twitter). https://x.com/elonmusk/status/1798937746624631249

Introduction to materials selection



Not stiff enough
⇒ **Need a higher E**

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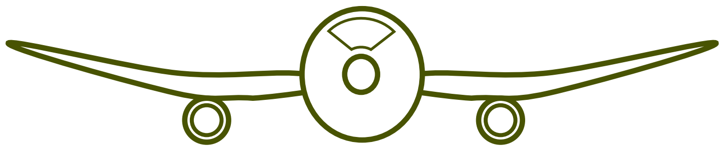

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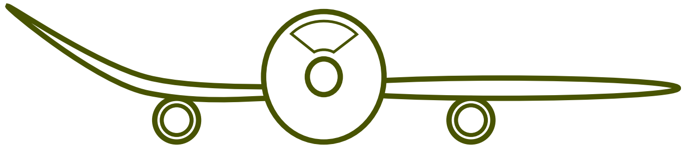

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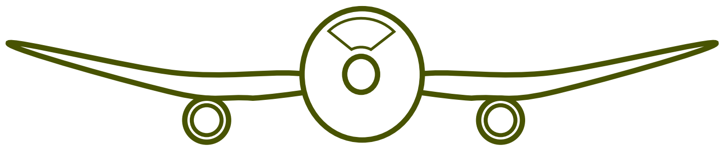

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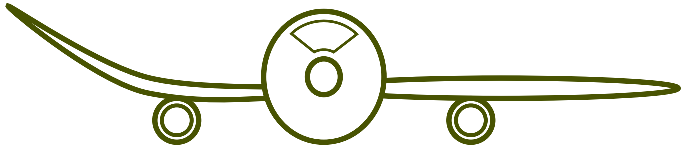

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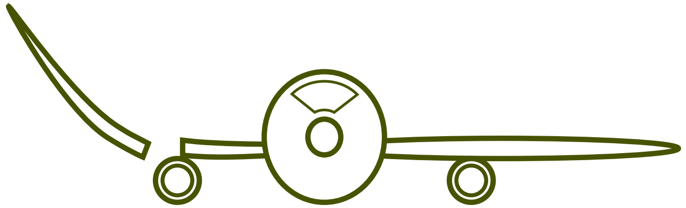

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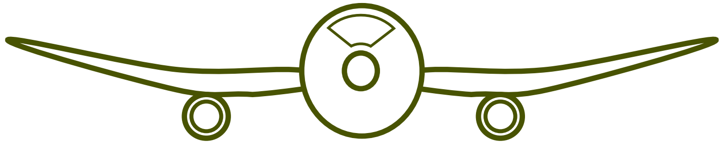

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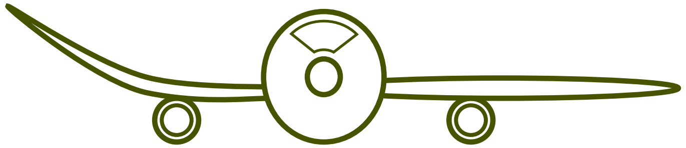

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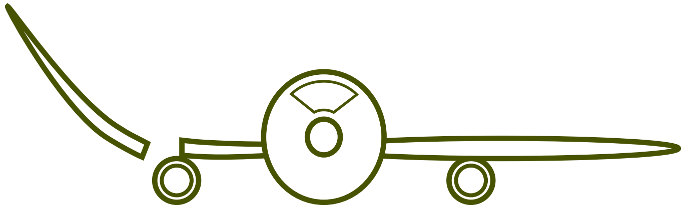

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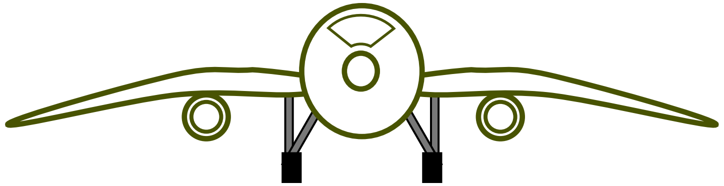

Too heavy
⇒ **Need a lower ρ**

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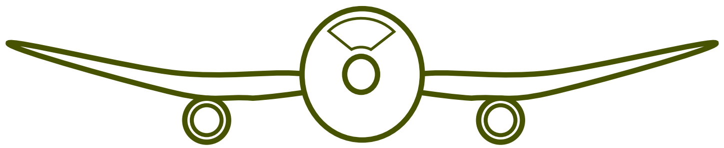

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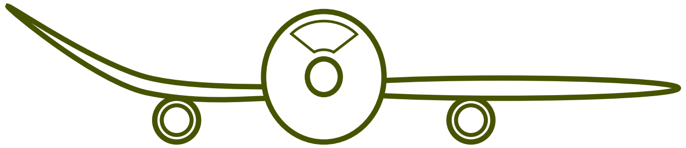

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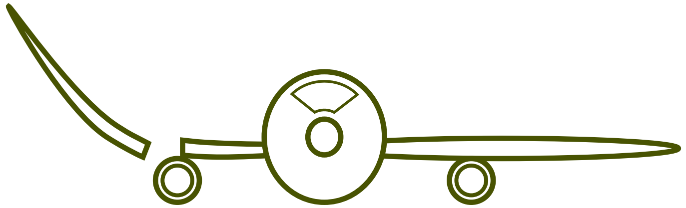

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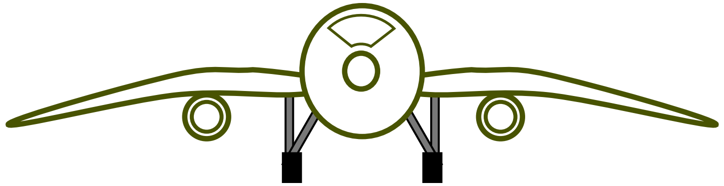

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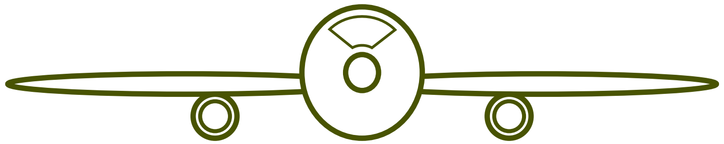

Stiff, strong, tough, light
⇒ **Everything is OK!**

Deformable / non-deformable

Solid

Non-deformable
(**Brittle**)

Deformable / non-deformable

Solid

Non-deformable
(**Brittle**)

Deformable
(**Ductile**)

Deformable / non-deformable

Solid | Liquid

Non-deformable
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Too deformable




Deformable / non-deformable

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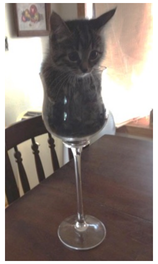


Ig-Nobel 2017, Marc-Antoine FARDIN (ENS Lyon)

The evolution of engineering materials

Engineers face 40,000 to 80,000 materials.
Selection must be progressively refined.

Ashby, M. F. (2005). *Materials Selection in Mechanical Design* (3rd ed.). Oxford: Elsevier

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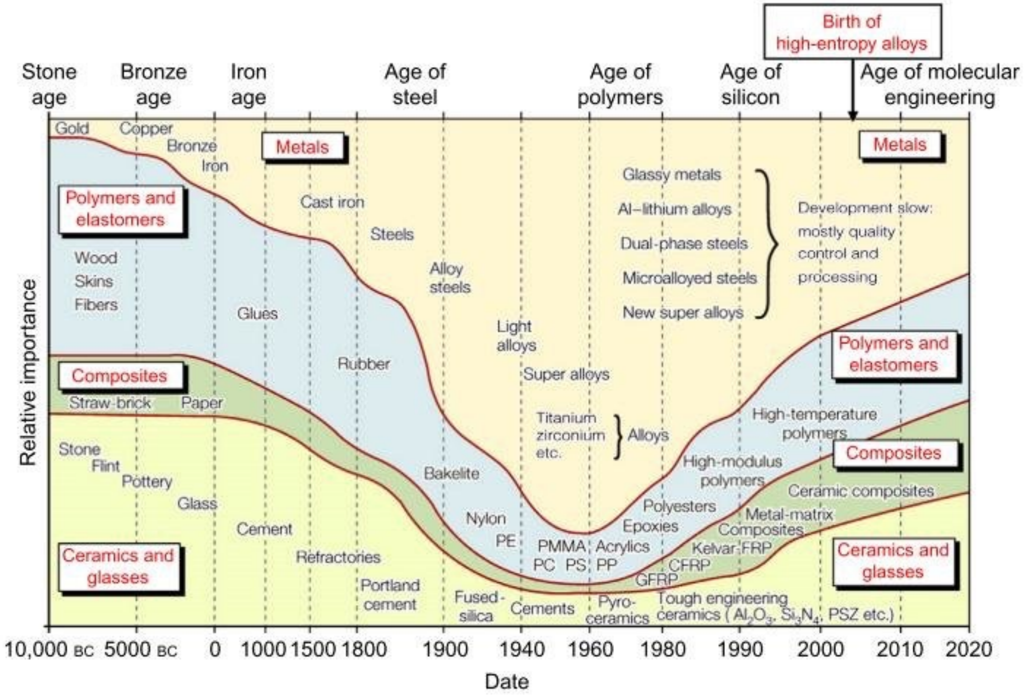

❖ **Human eras are named after materials:**
Stone Age, Bronze Age, Iron Age

❖ **Today is the age of advanced materials:**
Diverse, fast-evolving, high-performance

❖ **Since the 1960s:**
Rise of polymers, composites, advanced ceramics
❖ Metals (especially steel) still dominate but are no longer the sole focus.

❖ **The pace of materials innovation is unprecedented!**

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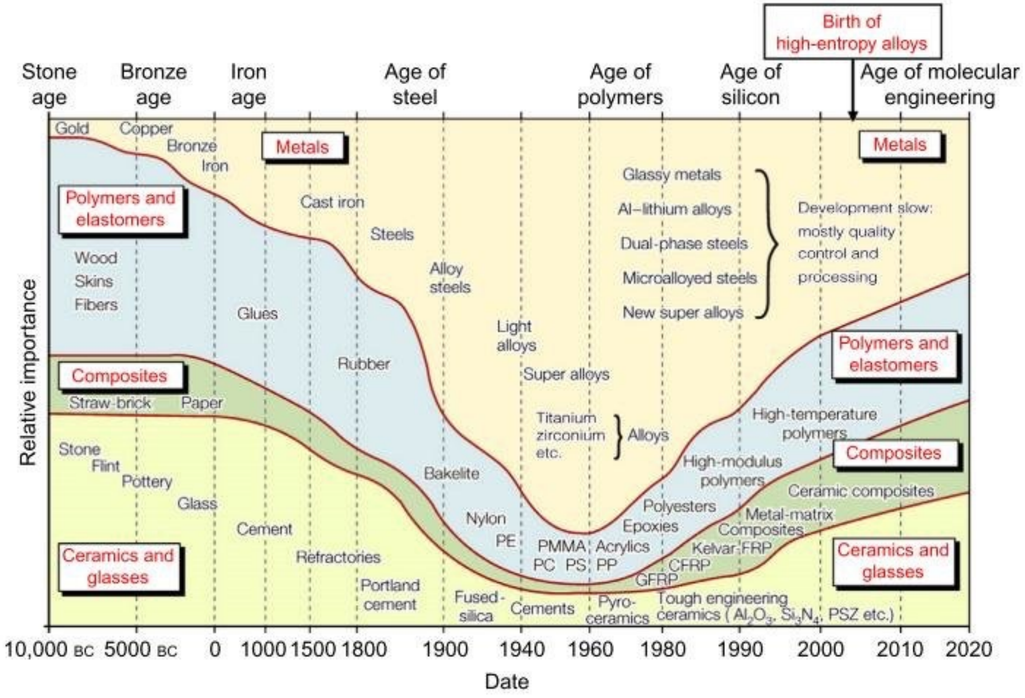

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↳ Engineers must stay informed or risk missing major opportunities!

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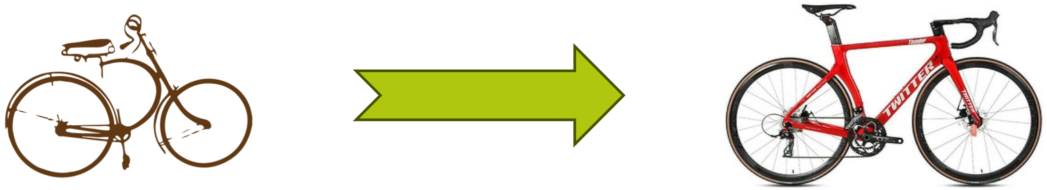
Example of the bicycle frames



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~1900							

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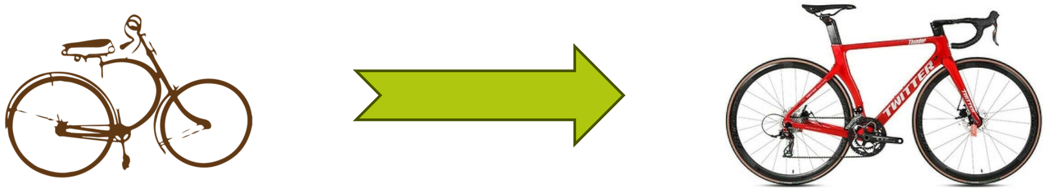

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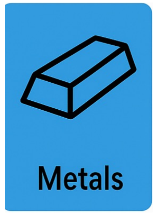
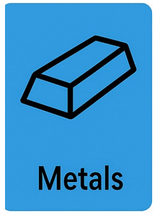
2000 – present	Carbon composite (fiber + polymer matrix)	Ultra-light, free-form shapes, directional stiffness, integrated design possibilities	High cost, complex manufacturing, limited recyclability	~€60–150/kg	~0.7–1.2 kg	Variable (tunable: stiff or compliant depending on fiber layout)	Simultaneous optimization of weight, stiffness, and comfort via anisotropic design

The classes of materials



❖ **Metals**

The classes of materials



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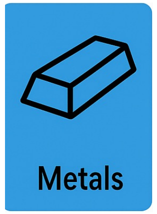

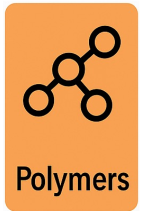

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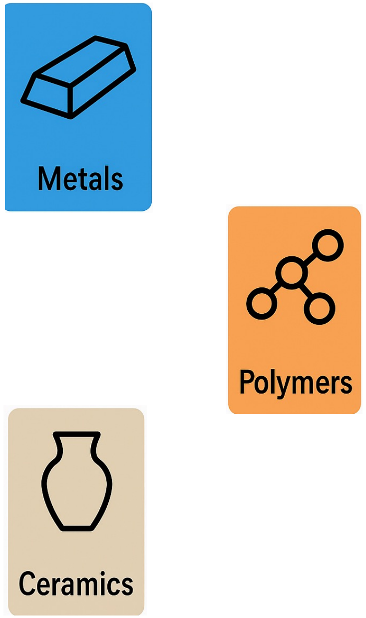

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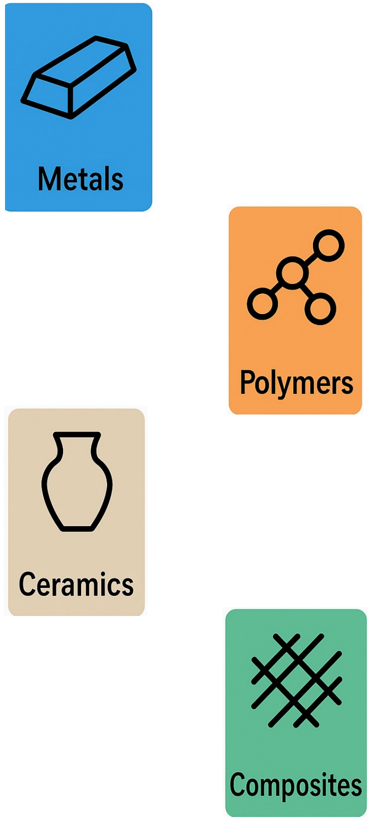

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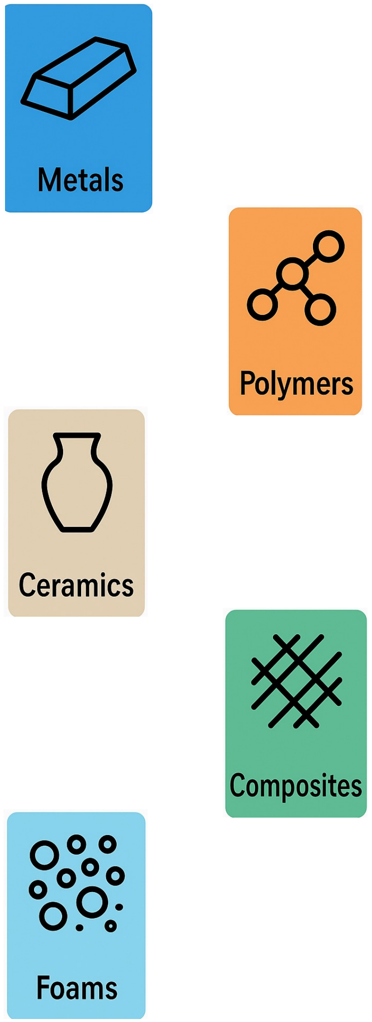

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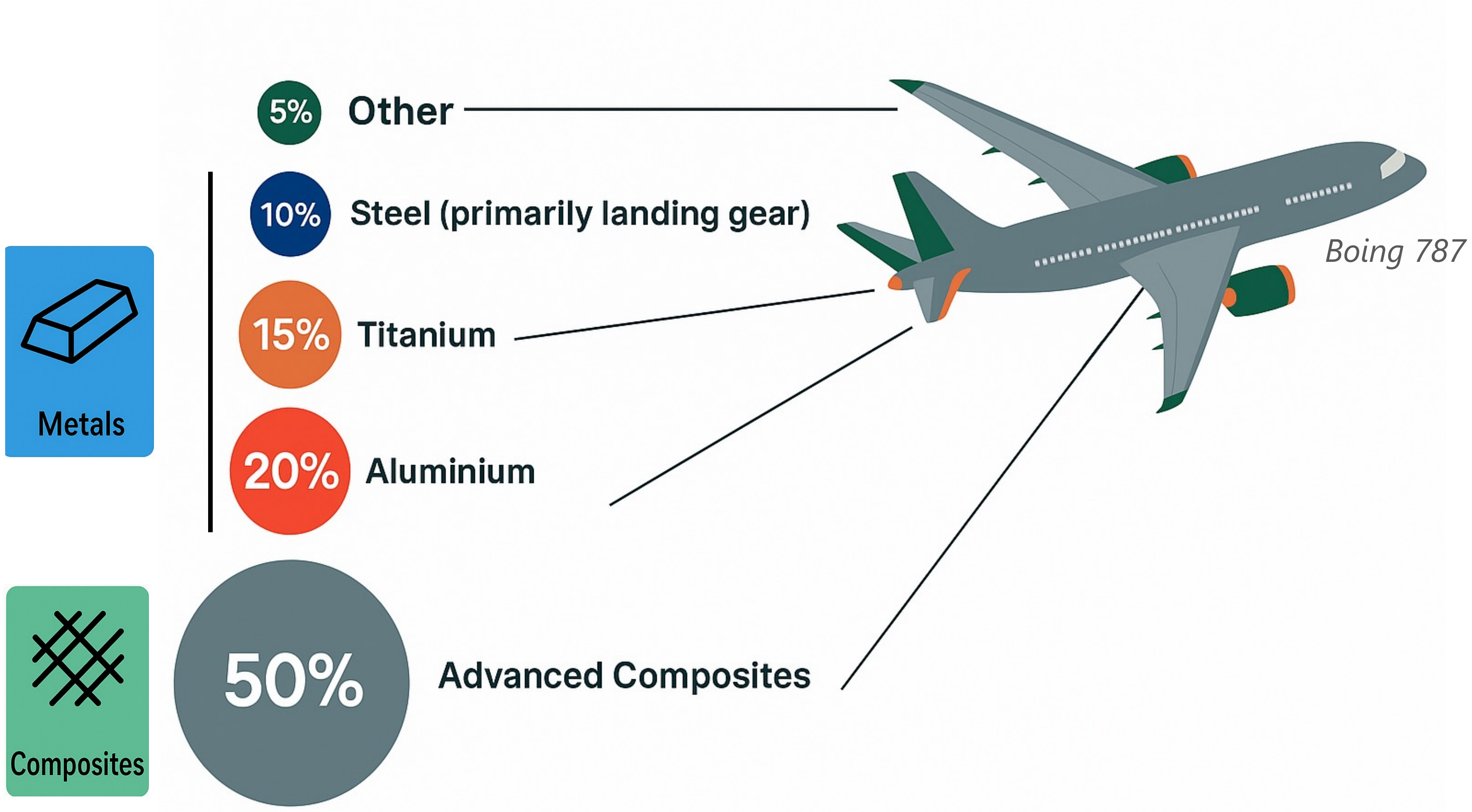
- **Foams**
  - Foams are materials that contain a large volume fraction of gas-filled pores within a solid matrix, making them very lightweight and often good for energy absorption or insulation.

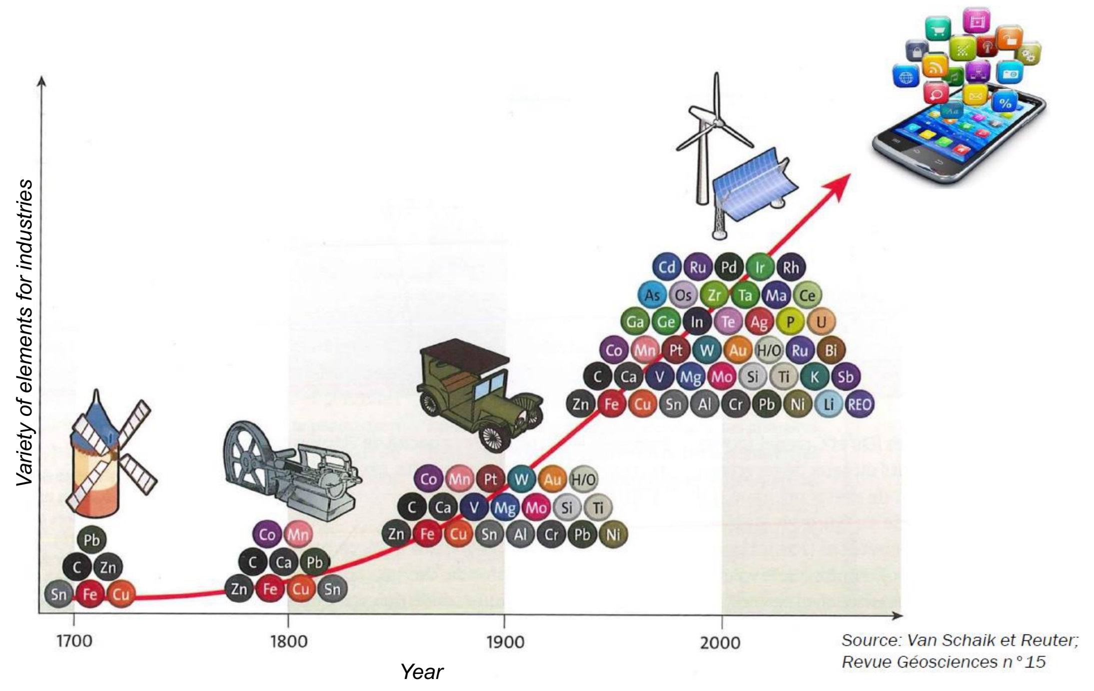
Materials for the aeronautic industry

45 %

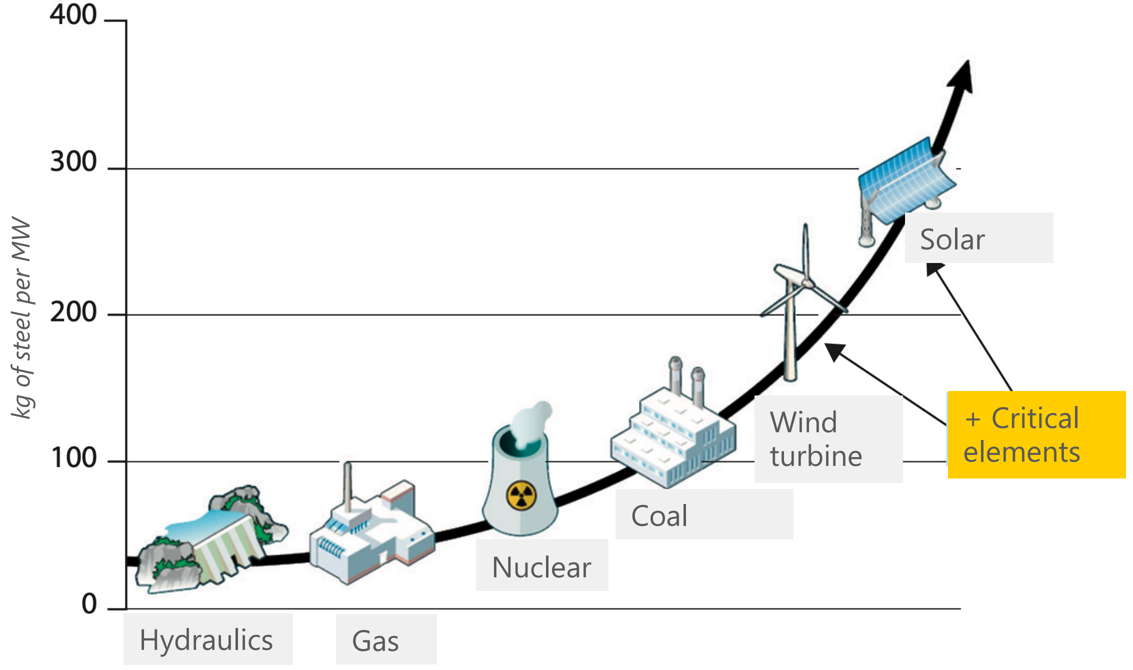


K. Bilisik et al. (2018). *Applications of Glass Fibers in 3D Preform Composites*

Materials for the electronics and energy industries

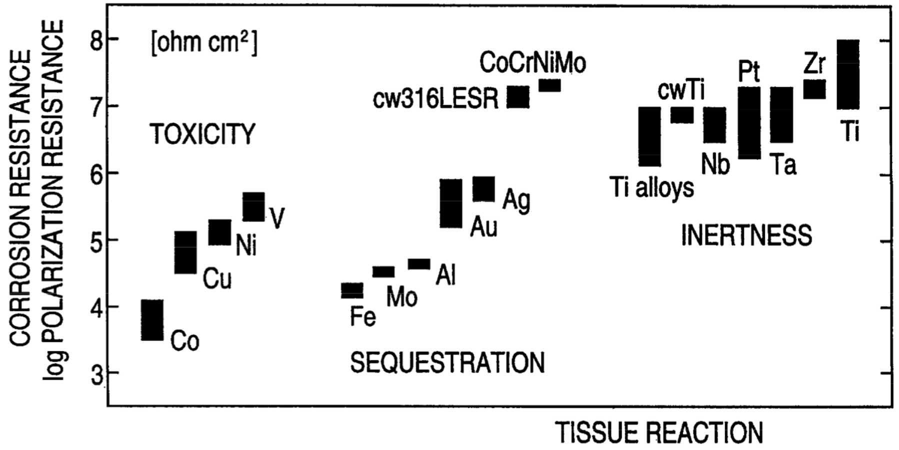


Source: Van Schaik et Reuter; Revue Géosciences n°15



Goffé et al. (2018) Fondation de la maison de la chimie; *Les matériaux stratégiques pour l'énergie*

Elements for the biomedical industry



❖ Toxicity:

- The ions that may be released during the use of the device trigger an immune response in the body, such as an allergy or inflammation.

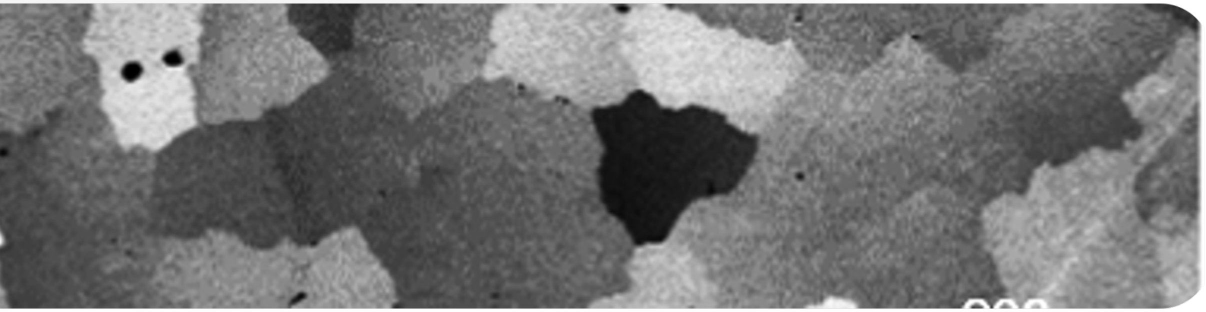
❖ Sequestration:

- The implant and the surrounding tissue become separated by a fibrous layer with very poor mechanical properties, which generally leads to implant failure because it is no longer properly integrated into the body.

❖ Inertness:

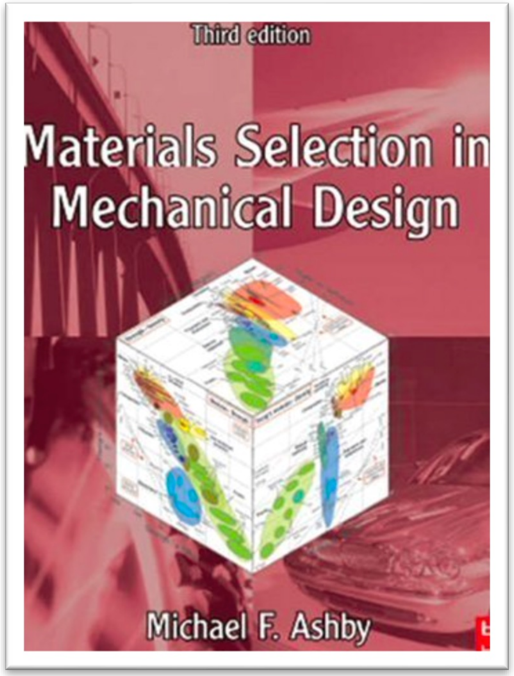
- These elements do not trigger any reaction from the body and allow the implant to be preserved under optimal conditions.

S.G. Steinmann (1996) Injury; *Metal implants and surface reactions*



The Ashby method: step-by-step

The general method of Ashby



Ashby, M. F. (2005)
Materials Selection in Mechanical Design
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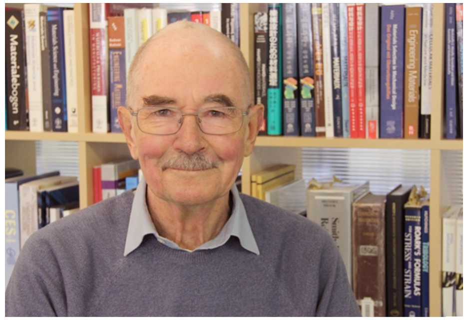
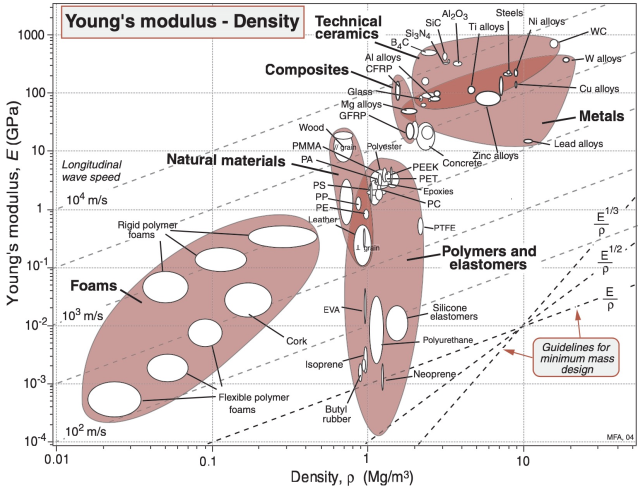
- Michael F. Ashby (1935-)
  - British metallurgical engineer





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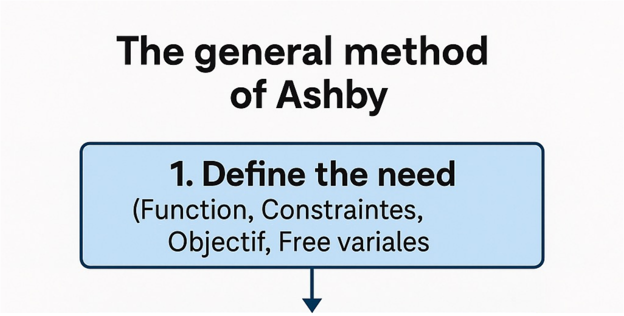
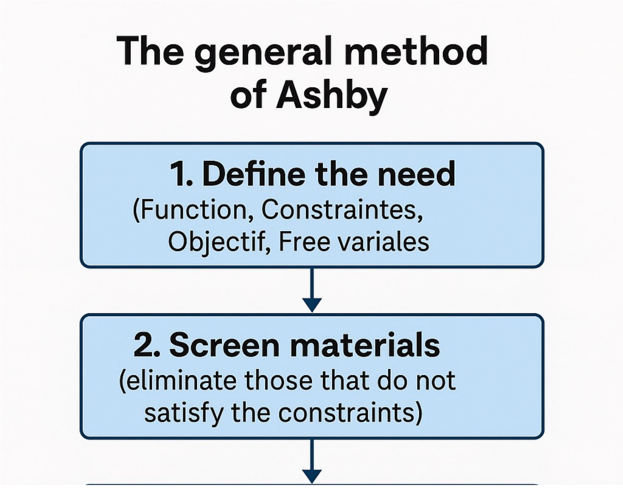


❖ Step 1: Define the need

- Identify the function of the component (e.g., support a load, insulate, conduct heat).
- Establish constraints (must-have properties: e.g., operating temperature, corrosion resistance, shape, cost ceiling).
- Clarify the objective (what you want to minimize or maximize: mass, cost, energy loss, stiffness, etc.).
- Determine the free variables (dimensions, material, design parameters you are allowed to change).

Ashby, M. F. (2005). *Materials Selection in Mechanical Design* (3rd ed.). Oxford: Elsevier

The general method of Ashby



❖ Step 2: Screen materials

- Use databases to eliminate all materials that fail to meet the constraints.
- This can drastically reduce the number of viable candidates (from thousands to dozens).
- Often done using simple threshold filters (e.g., operating temperature >150°C).

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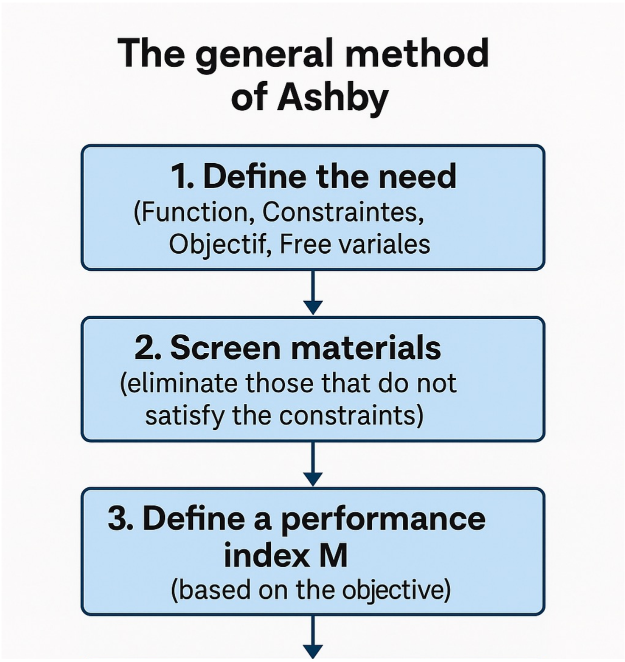

❖ Step 3: Define a performance index M

- An index M expresses how well a material performs relative to the objective.
- Derived from physical models (e.g., bending stiffness, thermal resistance).
- Examples:
  - Minimize mass of a beam:

$$\max\left\{M = \frac{\sqrt{E}}{\rho}\right\}$$

  - Maximize energy storage in a spring:

$$\max\left\{M = \frac{UTS^2}{E}\right\}$$

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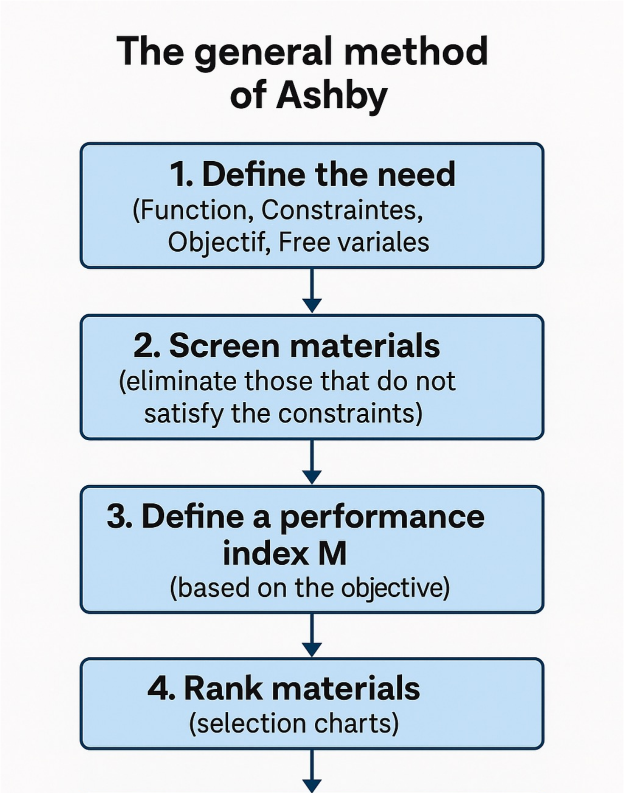
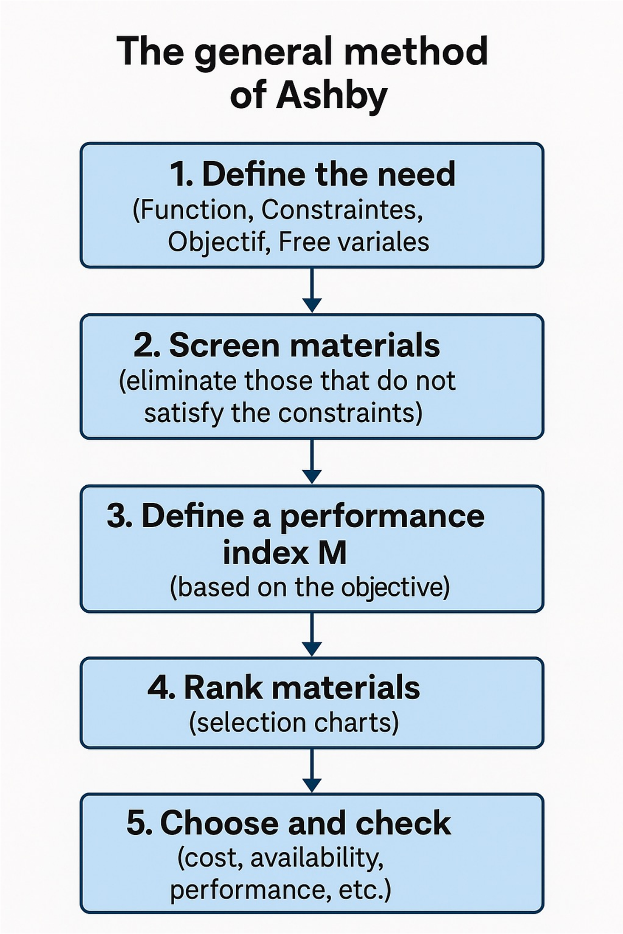


❖ Step 4: Rank materials

- Use Ashby charts (e.g., E vs ρ, UTS vs cost) with lines of constant M.
- These charts help visualize trade-offs and identify top performers.
- The "best" materials lie furthest along the desired line of M.

Ashby, M. F. (2005). *Materials Selection in Mechanical Design* (3rd ed.). Oxford: Elsevier

The general method of Ashby

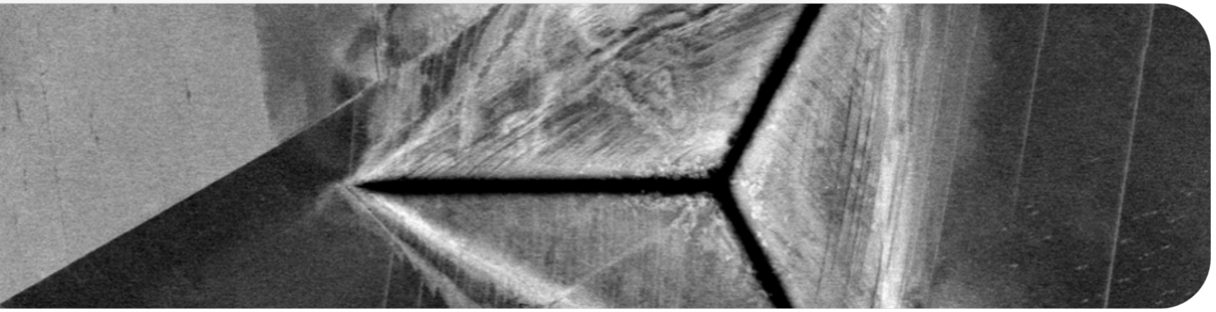


❖ **Step 5: Choose and check**

- Refine selection by considering:
  - Manufacturability
  - Availability
  - Environmental impact
  - Cost (real, not theoretical)
  - Compatibility with other parts

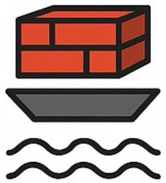
- Prototype and test if necessary.

Ashby, M. F. (2005). *Materials Selection in Mechanical Design* (3rd ed.). Oxford: Elsevier



Some mechanical properties & performance indices

The density (ρ)



Material class	Approx. density (kg/m^3)
Foams	10–100
Polymers	900–1,500
Aluminum alloys	~2,700
Steels	~7,800
Titanium alloys	~4,500
Composites (carbon)	1,500–1,800
Ceramics	2,000–6,000

- **Definition:**
  - It is the mass per unit volume of a material:

$$\rho = \frac{m}{V}$$

- **Unit:** kg/m^3
- **Directly affects the mass of structures and components**
- **Critical for applications where lightweighting is essential**
  - Aerospace, automotive, sports)
- **Influences inertia, energy consumption, and handling in moving parts**

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What is stress?

- **In biology:**
  - The set of responses produced by an organism when subjected to pressures from its environment.
  - These responses always depend on how the individual perceives the pressures it experiences.

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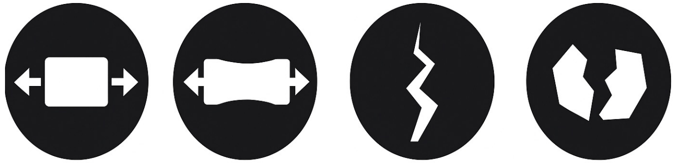

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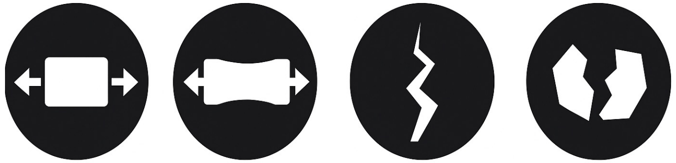

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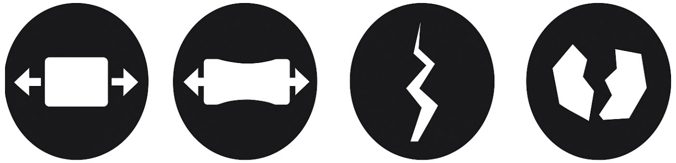

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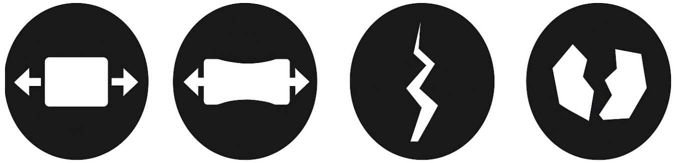

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➯ Stress is the response to pressure, in organisms as in materials.
➯ **It is not a measurement!**

The Young modulus (E)

Material class	Approx. Young modulus (GPa)
Foams	0.001–0.1
Polymers	1–5
Aluminum alloys	~70
Steels	~200
Titanium alloys	~120
Composites (carbon)	up to 600
Ceramics	100–400

- **Definition:**
  - It measures the stiffness of a material in the elastic (reversible) regime.
  - It is defined as the ratio of stress to strain in linear elastic deformation:
    - $E = \frac{\sigma}{\varepsilon_e}$
- **Unit:** Pa
- **Determines how much a material elongates or compresses under load**
- **Critical in:**
  - Structural rigidity (beams, trusses, panels)
  - Vibration control
  - Precision mechanisms

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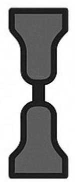
The yield strength ($\sigma_{0.2}$/ $R_{p\ 0.2}$)



Material class	Approx. yield strength (MPa)
Foams	0.01–5
Polymers	10–100
Aluminum alloys	150–400
Steels	250–1500
Titanium alloys	800–1200
Composites (carbon)	500–1500
Ceramics	n.a.

- **Definition:**
  - The stress at which a material begins to deform plastically, as determined by the 0.2% offset method.
  - Below this point, deformation is considered elastic and reversible.
- **Unit:** Pa
- **Determines the maximum stress a material can withstand without permanent deformation**
- **Critical in:**
  - Sets the limit for safe elastic behavior
  - Ensures structural integrity under expected loading conditions
  - Determines the minimum cross-sectional area required to carry loads
  - Impacts durability, reliability, and performance over time

Ashby, M. F. (2005). Materials Selection in Mechanical Design (3rd ed.). Oxford: Elsevier

Some vocabulary

- **Elastic behavior**
  - Limit of elasticity
    - ✓ Maximum stress a material can withstand without any permanent deformation.
    - ✓ Conceptual limit; not always easy to measure precisely.

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    - ✓ General term for the stress at which plastic deformation begins.
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    - ✓ A well-defined point where plastic deformation starts suddenly, sometimes followed by a drop in stress.
    - ✓ Observed in specific materials like mild steels, with upper and lower yield points.

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  - Yield strength
    - ✓ Standardized engineering value of yield stress.
    - ✓ Typically defined by the 0.2% offset method ($\sigma_{0,2}$), especially for materials without a clear yield point.

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❖ Plastic flow

- Flow stress
  - ✓ Stress required to maintain plastic deformation at a given plastic strain.
  - ✓ Increases with strain hardening; often modeled as $\sigma = K\varepsilon^n$

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The ultimate tensile strength (UTS)

Material class	Approx. UTS (MPa)
Foams	0.01–2
Polymers	20–150
Aluminum alloys	200–550
Steels	400–2000
Titanium alloys	900–1400
Composites (carbon)	600–2000 (direction-dependent)
Ceramics	100–1000

- **Definition:**
  - The maximum stress a material can withstand in tension before necking or failure occurs.
  - It is the peak point on the engineering stress–strain curve.
- **Unit:** Pa
- **Critical in:**
  - Represents the upper limit of a material's load-bearing capacity
  - Relevant for failure analysis and fracture prediction
  - Used when plastic deformation is acceptable but fracture must be avoided
  - Critical in applications involving extreme loading, impact, or stress concentrations

Ashby, M. F. (2005). Materials Selection in Mechanical Design (3rd ed.). Oxford: Elsevier

The elongation (%EL)

Material class	Approx. %EL (%)
Foams	< 5
Polymers	10–800
Aluminum alloys	5–20
Steels	10–40
Titanium alloys	10–30
Composites (carbon)	1–2 (direction-dependent)
Ceramics	< 1

- **Definition:**
  - The strain at fracture *i.e.*, how much a material stretches before breaking under tension
  - It includes both elastic and plastic deformations.
- **Unit:** %
- **Importance in design:**
  - Indicates the ductility of a material
  - Critical for applications requiring formability, bending, or energy absorption
  - Used in cold forming, sheet metal design, and impact-resistant components
  - Helps predict fracture behavior:
    - ✓ High elongation: ductile, absorbs energy before breaking
    - ✓ Low elongation: brittle, sudden failure

Ashby, M. F. (2005). Materials Selection in Mechanical Design (3rd ed.). Oxford: Elsevier

The shear modulus (G)

Material class	Approx. G (GPa)
Foams	0.001–0.05
Polymers	0.1–1
Aluminum alloys	~25
Steels	~80
Titanium alloys	~40
Composites (carbon)	10 – 40 (direction-dependent)
Ceramics	20–150

- **Definition:**
  - It quantifies a material's resistance to shape change (angular distortion) at constant volume.
  - The ratio of shear stress to shear strain in the elastic region:

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

- **Unit:** Pa
- **Importance in design:**
  - Critical for components under torsion or shear loading
  - Used to predict angular deformation in mechanical systems
  - Essential in mechanical modeling, vibration analysis, and composite layup calculations

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The toughness (U_T)

Material class	Approx. toughness (MJ/m^3)
Foams	< 0.1
Polymers	1–5
Aluminum alloys	5–20
Steels	20–100
Titanium alloys	30–120
Composites (glass fibers)	0.2–2
Ceramics	0.01–0.1

- **Definition:**
  - The amount of energy per unit volume a material can absorb before fracturing
  - It assumes a defect-free material.
  - Combines both strength and ductility
  - Approximated as the total area under the stress–strain curve

$$U_T = \int_0^{\varepsilon_r} \sigma \mathrm{d}\varepsilon$$

- **Unit:** J/m^3
- **Importance in design:**
  - Indicates a material's resistance to fracture under impact or sudden loads
  - Crucial in safety-critical applications (e.g. automotive, aerospace, pressure vessels)
  - Relevant for crash resistance, ballistic protection, and structural reliability

Ashby, M. F. (2005). Materials Selection in Mechanical Design (3rd ed.). Oxford: Elsevier

The resilience (U_r)

Material class	Approx. resilience (MJ/m³)
Foams	0.001–0.01
Polymers	0.05–1
Aluminum alloys	0.2–1.0
Steels	1–5
Titanium alloys	2–6
Composites (glass fibers)	1–10 (direction-dependent)
Ceramics	< 0.01

- **Definition:**
  - The amount of energy per unit volume a material can absorb without permanent deformation
  - It is the area under the elastic (linear) part of the stress–strain curve

$$U_r = \int_0^{\varepsilon_e} \sigma \mathrm{d}\varepsilon = \frac{1}{2}\sigma\varepsilon_e = \frac{\sigma^2}{2E}$$

- **Unit:** J/m³
- **Importance in design:**
  - Resistance to reversible deformation
  - Important in springs, shock absorbers, dynamic systems
  - Prevents elastic failure

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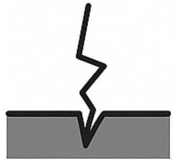
The fracture toughness (K_{1C})



Material class	Approx. K_{1C} (MPa·m$^{1/2}$)
Foams	< 0.05
Polymers	1–5
Aluminum alloys	20–40
Steels	50–150
Titanium alloys	40–100
Composites (glass fibers)	10–30 (in plan)
Ceramics	0.5–5

- **Definition:**
  - The ability of a material containing a crack to resist fracture
  - Mode I critical stress intensity factor

$$K_{1C} = Y\sigma_r\sqrt{\pi a_c}$$

- **Unit:** MPa·m$^{1/2}$
- **Importance in design:**
  - Essential for components where flaws or cracks may exist
  - Crucial in aerospace, nuclear, biomedical, and pressure equipment
  - Helps assess damage tolerance and fail-safe behavior

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Why do we need a performance index (M)?

- Engineers must choose materials that best meet the design objective.

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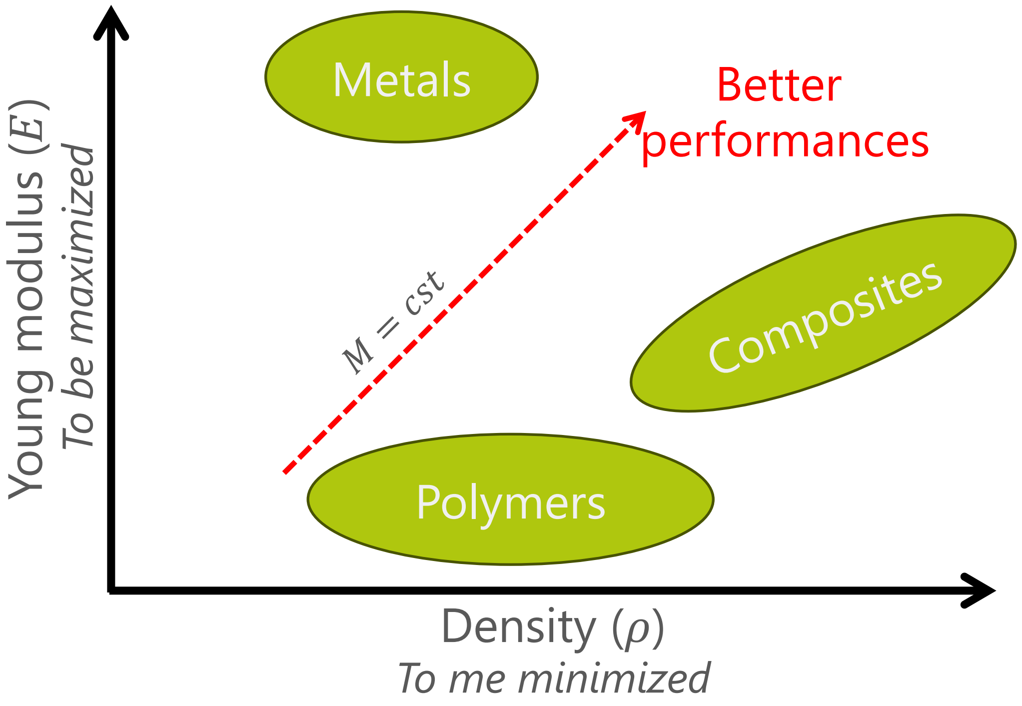

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Example: Light stiff beam in bending

- **Objective:**
  - Minimize mass for a given stiffness

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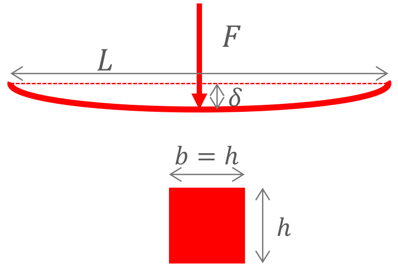
  - Mass: $m = ?$



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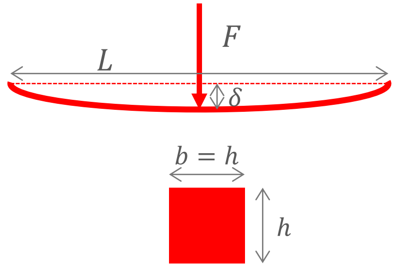
- **Objective:**
  - Minimize mass for a given stiffness
- **Model:**
  - Deflection: $\delta = \frac{FL^3}{48EI}; I = \frac{bh^3}{12} = \frac{h^4}{12}$
  - Mass: $m = \rho LA$



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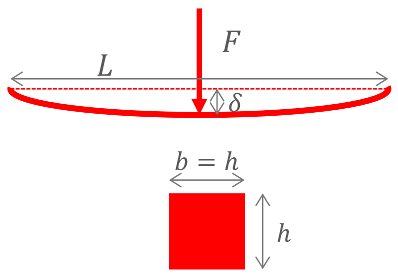
  - Mass: $m = \rho LA$
- **Constraints:**
  - Stiff: $\delta < \delta_{max}$
  - Geometry: $I \geq \frac{FL^3}{48E\delta_{max}} \propto \frac{1}{E}$



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  - Often, geometry is fixed or optimized
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- Group material terms into an expression M
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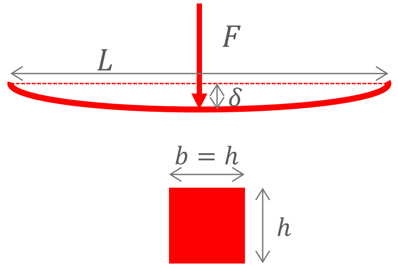
Example: Light stiff beam in bending

- **Objective:**
  - Minimize mass for a given stiffness
- **Model:**
  - Deflection: $\delta = \frac{FL^3}{48EI}; I = \frac{bh^3}{12} = \frac{h^4}{12}$
  - Mass: $m = \rho LA$



- **Constraints:**
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  - Geometry: $I \geq \frac{FL^3}{48E\delta_{max}} \propto \frac{1}{E}$
- **Rearranged:**
  - Use minimal I for given stiffness E, assuming fixed L and square A: $A = h^2 = \sqrt{12I}$
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How to construct a performance index (M)

- General from:

$$M = \frac{Property\ to\ be\ maximized}{Penalty\ term}$$

- Define the function
  - What does the component do? (e.g., support a load, store energy, conduct heat…)
- Write a physical model
  - Express the performance objective using fundamental equations.
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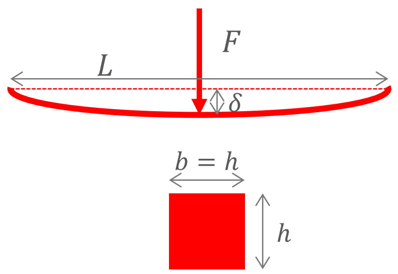

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  - Always a quantity to be maximized

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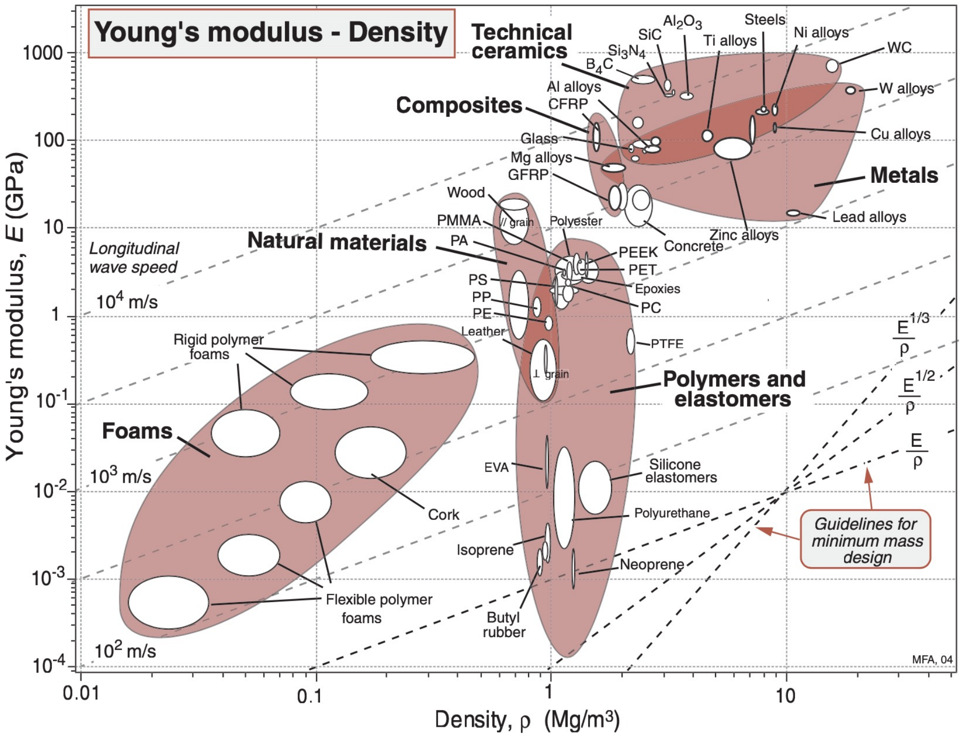
How to construct a performance index (M)



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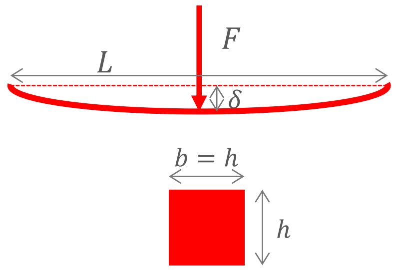

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Key environmental criteria for materials

- **Main environmental indicators:**
  - Embodied energy (MJ/kg)
    - Total energy to produce 1 kg of material
  - Carbon footprint (kg CO_2/kg)
    - Greenhouse gases emitted during production
  - Recyclability
    - Can the material be recovered and reused?
  - Toxicity and health impact
    - Are harmful substances used or released?
  - End-of-life options
    - Reuse, recycling, incineration, landfill?
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    - Is the material fossil-based or bio-based?

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Example of life cycle analysis

Bike frame (steel vs. aluminum)

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Aspect	Steel frame	Aluminum frame
Young's modulus (E)	210 GPa	70 GPa
Density (ρ)	7850 kg/m^3	2700 kg/m^3
Stiffness ratio	1 (reference)	1/3
Required volume	1 (reference)	**×3** (to match stiffness)
Estimated frame mass	~2.5 kg	~2.6 kg **(×1.03)**
Embodied energy	~25 MJ/kg × 2.5 kg = ~62 MJ	~200 MJ/kg × 2.6 kg = ~520 MJ **(×8)**
CO_2 footprint	~5 kg CO_2	~30 kg CO_2 **(×5)**
Use-phase impact	Higher (heavier to ride)	Lower (lighter)
Recyclability	Good	Excellent, but higher energy needed

↳At fixed volume: similar mass, higher embodied energy.
↳At fixed stiffness Al wins; ~40% lighter than steel.
↳ Choice depends on the design scenario.

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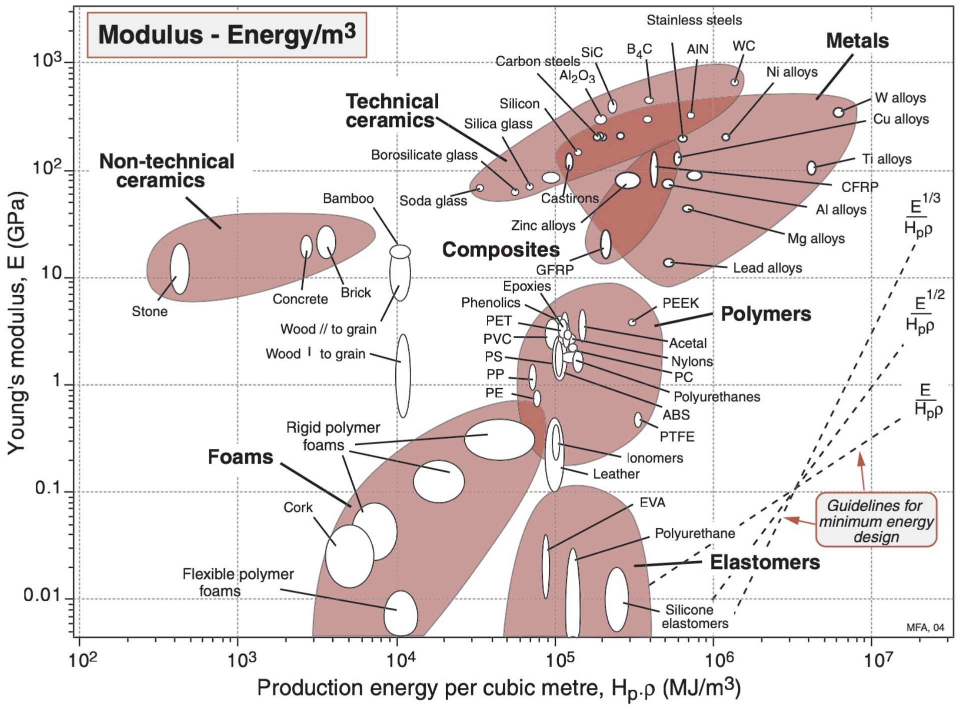

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Shape and microstructure matter too

- **Shape factor**
  - A shape factor quantifies the gain in performance due to geometry compared to a reference shape (typically a solid square section of same area):

$$\phi = \frac{Performance\ (real\ shape)}{Performance\ (ref\ shape)}$$

  - Shape and material can be selected together using hybrid indices, like:

$$M = \phi \frac{\sqrt{E}}{\rho}$$

  - There's no single "best shape". It depends on the type of loading:
    - Bending ⇒ maximize I; Torsion ⇒ maximize J; Buckling ⇒ maximize I, minimize L

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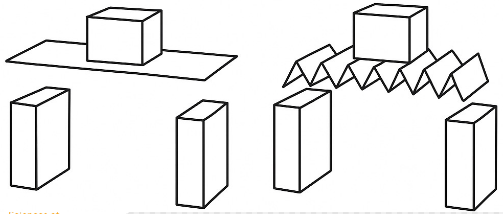
❖ Why it matters?

- Optimizing shape gives mass savings without changing material.
- Shape selection is essential in aerospace, transport, architecture, etc.



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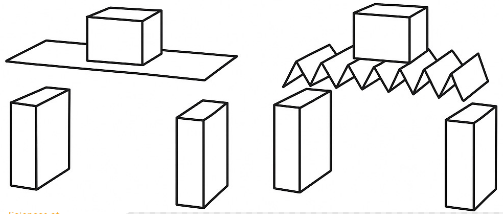
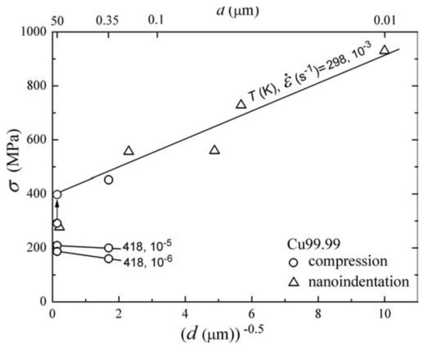
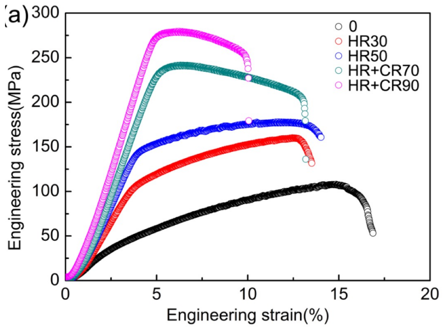


❖ Microstructure:

- A material's microstructure (grain size, phase distribution, defects) can significantly affect its mechanical, thermal, and electrical properties.
- Two samples with the same composition can behave very differently if their microstructures differ.
- Processing (e.g., forging, annealing, quenching, rolling) alters the microstructure and therefore the performance.
- Grain refinement increases strength (Hall–Petch effect) but may reduce ductility.
- Heat treatment can increase hardness or toughness by changing phase fractions (e.g., martensite vs ferrite).
- Work hardening, precipitation hardening, and phase transformation are all microstructure-driven strategies.





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Thanks for your listening!

If you need further information:

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LABORATOIRE D'ÉTUDE DES MICROSTRUCTURES ET DE MÉCANIQUE DES MATÉRIAUX

UNIVERSITÉ DE LORRAINE

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