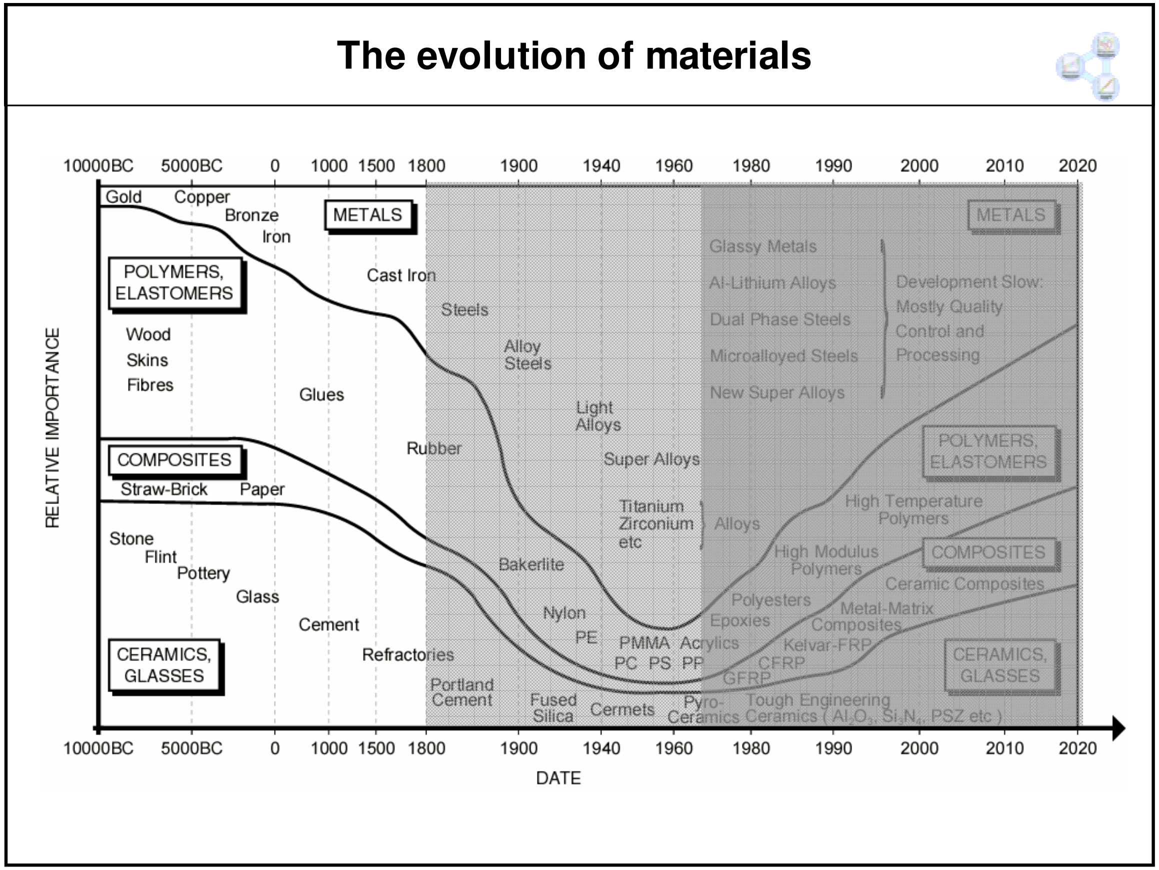
Materials Selection : Engineering Materials, Properties and Selection Methodology

ME 423: Machine Design
Instructor: Ramesh Singh

Outline

- Engineering Materials
- Material Properties
  - Mechanical Properties
  - Thermal Properties
  - Electrical Properties
  - Optical Properties
  - Eco-Properties

Evolution of Materials



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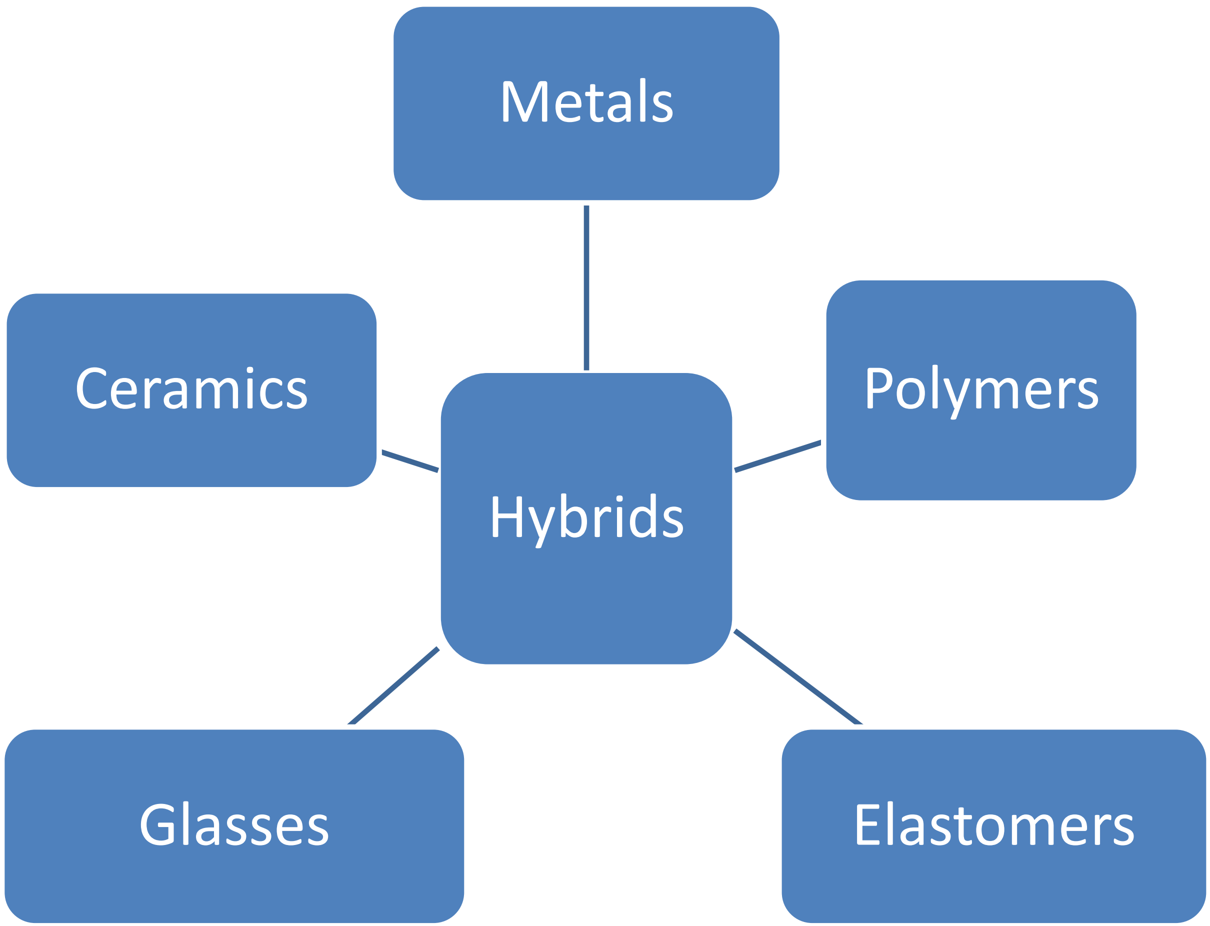
Classes of Engineering Materials



Materials

- Metals: Stiff materials with relatively high elastic moduli and exhibit ductility. Can be made strong by alloying, mechanical and heat treatments
- Ceramics and glasses: Materials with high moduli, but, brittle.
  - Tensile strength means the brittle fracture strength;
  - Compresssive strength is the brittle crushing strength (15x fracture strength).
  - Low tolerance for stress concentrations (like holes or cracks) or for high contact stresses (at clamping points, for instance)
  - Finds application in bearings and cutting tools
  - Large scatter in the properties

Materials

- *Polymers* and *elastomers:* Materials with low moduli
  - High strength can be as strong as metals
  - Elastic deflections can be large due to low moduli
  - They exhibit creep (time dependent deformation under constant load) even at room temperature
  - Very high strength-to-weight ratio
  - Can be made into complex shapes

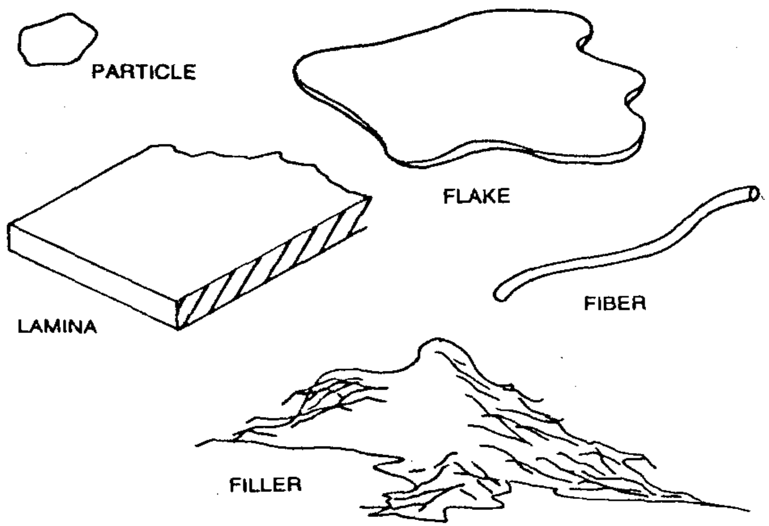
Materials:Composites

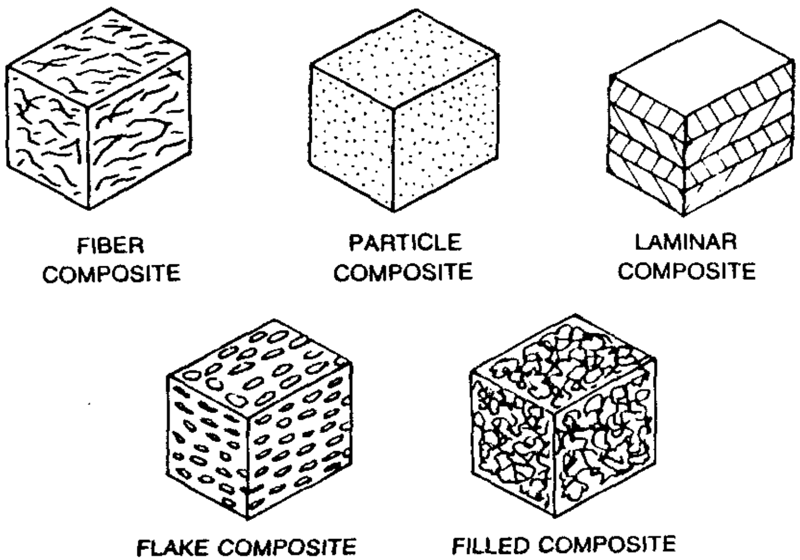
A composite material consists of two phases:

- Primary
  - Forms the matrix within which the secondary phase is imbedded
  - Any of three basic material types: polymers, metals, or ceramics
- Secondary
  - Referred to as the imbedded phase or called the reinforcing agent
  - Serves to strengthen the composite (fibers, particles, etc.)
  - Can be one of the three basic materials or an element such as carbon or boron

Types of composite materials

There are five basic types of composite materials: Fiber, particle, flake, laminar or layered and filled composites.





Classification of composite material

- **Metal Matrix Composites (MMCs)**
  - Mixtures of ceramics and metals, such as cemented carbides and other cermets
  - Aluminum or magnesium reinforced by strong, high stiffness fibers
- **Ceramic Matrix Composites (CMCs)**
  - Least common composite matrix
  - Aluminum oxide and silicon carbide are materials that can be imbedded with fibers for improved properties, especially in high temperature applications
- **Polymer Matrix Composites (PMCs)**
  - Thermosetting resins are the most widely used polymers in PMCs.
  - Epoxy and polyester are commonly mixed with fiber reinforcement

Classification of composite material

- Matrix material serves several functions in the composite
  - Provides the bulk form of the part or product
  - Holds the imbedded phase in place
  - Shares the load with the secondary phase

The reinforcing phase

- The imbedded phase is most commonly one of the following shapes:
  - Fibers, particles, flakes
- Orientation of fibers:
  - **One-dimensional**: maximum strength and stiffness are obtained in the direction of the fiber
  - **Planar:** in the form of two-dimensional woven fabric
  - **Random or three-dimensional:** the composite material tends to posses isotropic properties

The reinforcing phase

Types of phases

- Currently, the most common fibers used in composites are glass, graphite (carbon), boron and Kevlar 49.
  - Glass – most widely used fiber in polymer compositescalled glass fiber-reinforced plastic (GFRP)
    - E-glass – strong and low cost, but modulus is less than other (500,000 psi)
    - S-glass – highest tensile strength of all fiber materials (650,000 psi). UTS~ 5 X steel ; $\rho \sim 1/3$ x steel

The reinforcing phase

- Carbon/Graphite –Graphite has a tensile strength three to five times stronger than steel and has a density that is one-fourth that of steel.
- Boron – Very high elastic modulus, but its high cost limits its application to aerospace components
- Ceramics – Silicon carbide (SiC) and aluminum oxide (Al2O3) are the main fiber materials among ceramics. Both have high elastic moduli and can be used to strengthen low-density, low- modulus metals such as aluminum and magnesium
- Metal – Steel filaments, used as reinforcing fiber in plastics

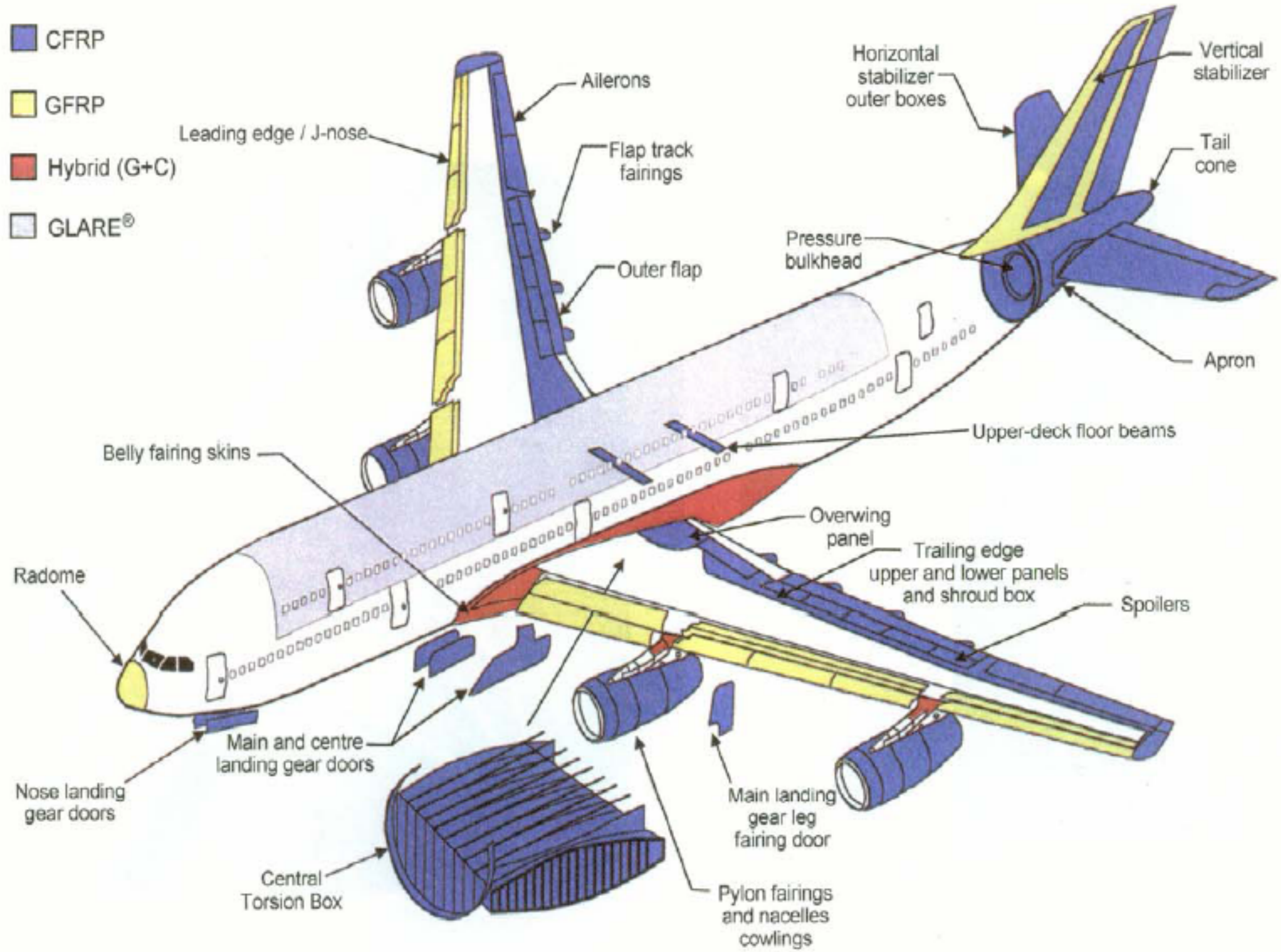


Plate 1: A380 composite materials application. Not shown: CFRP passenger floor panels and struts. *Some composite parts are bonded others are not*. Several metal parts are also bonded in modern civil and military aircrafts.

Automotive sectors

Lamborghini

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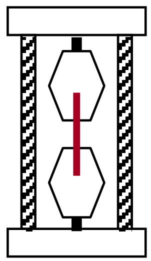
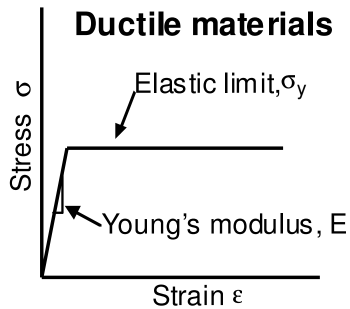
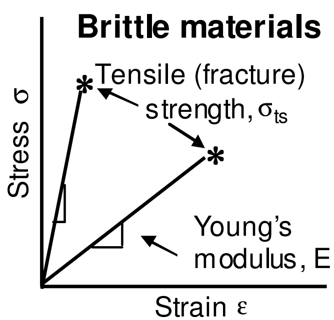
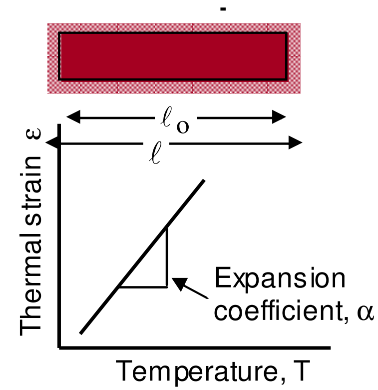
Mechanical Properties



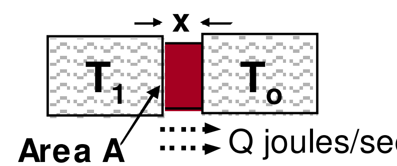


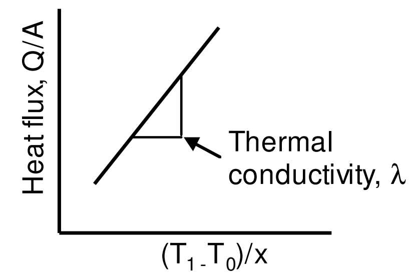


- General
  - Weight
  - Expense
- Mechanical
  - Stiffness: E (Gpa)
  - Strength: σ_y yield strength
  - Tensile strength: σ_t
  - Fracture toughness: K_{IC}
- Thermal
  - Expansion coefficient
  - Thermal conductivity
- Electrical
  - Conductivity
- Wear corrosion and Oxidation



Thermal conduction

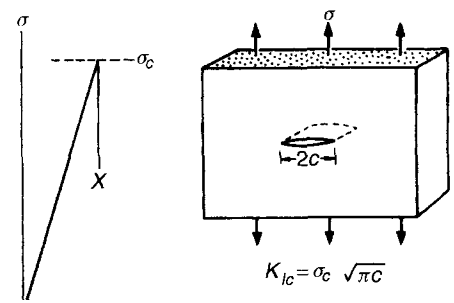




Fracture Toughness

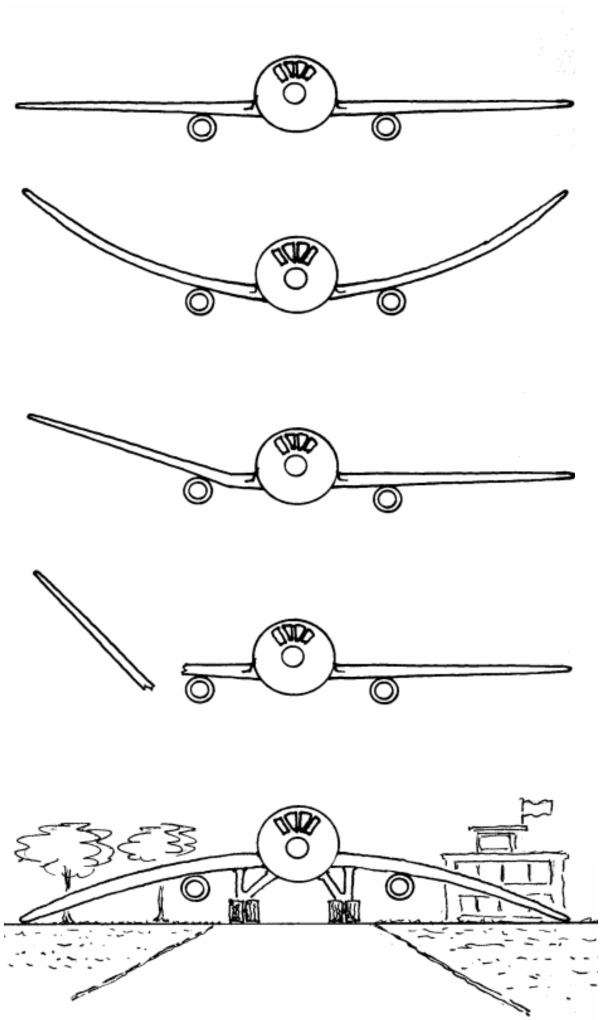
- Fracture toughness ($MPa\sqrt{m}$) measure of the crack resistance of the material

- $K_{Ic} = \beta \sigma_t \sqrt{\pi c}$



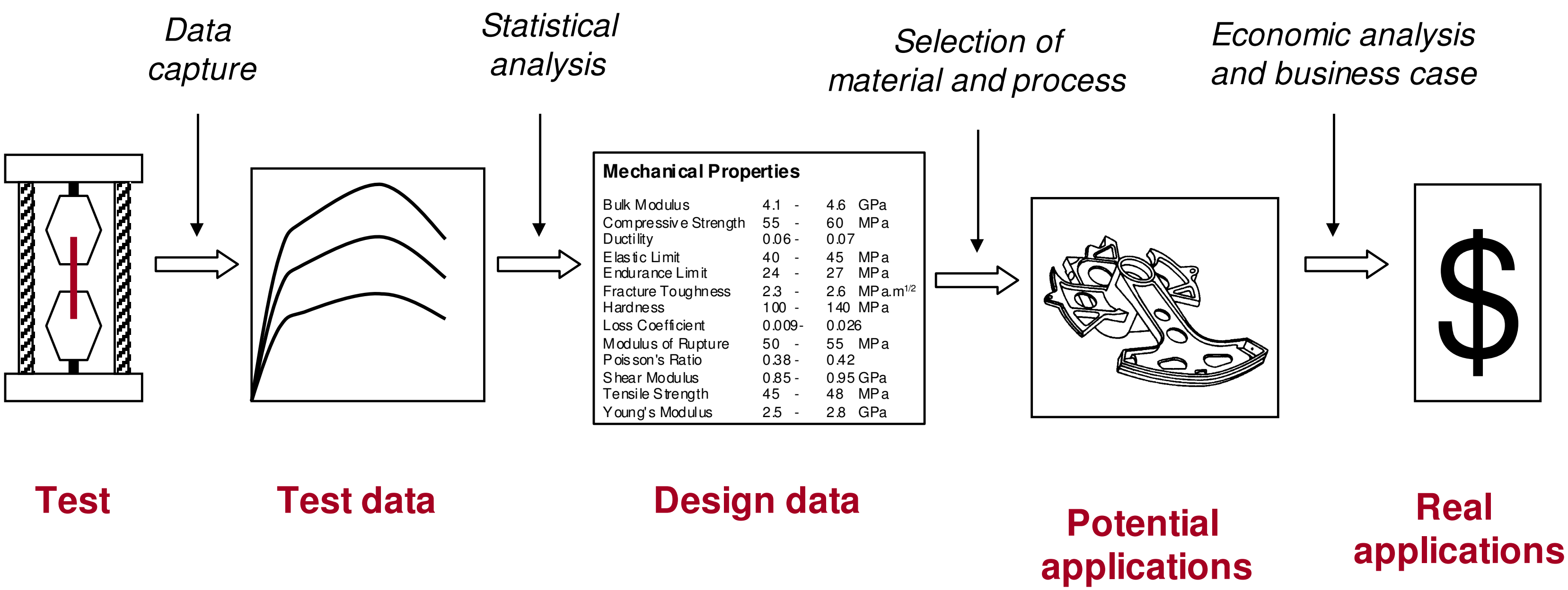
- The fracture toughness is determined by loading a sample with a known crack of length 2c
- Fracture toughness are typically well defined for brittle materials

Illustration of Mechanical Properties



- All right(Stiff, strong, tough, light)
- Not stiff enough (needs higher E)
- Not strong enough (needs higher σ_y)
- Not tough enough (needs higher K_{IC})
- Too heavy needs (needs lower density)

Materials



Characterization

Selection and Implementation

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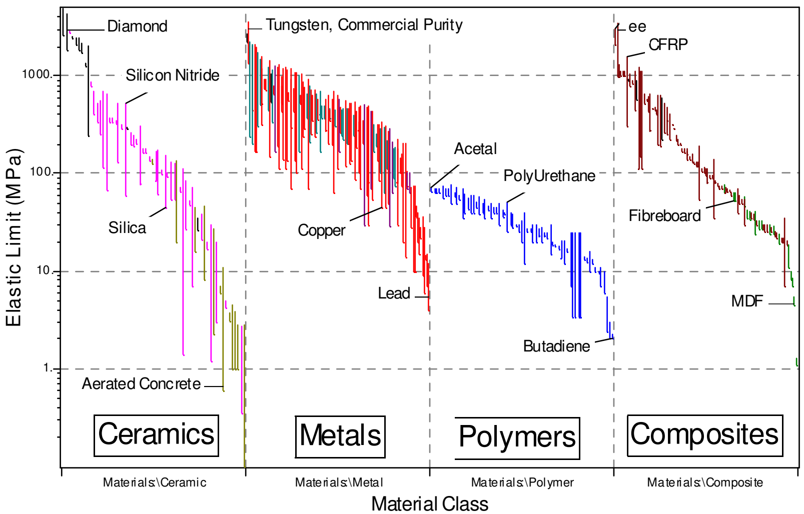
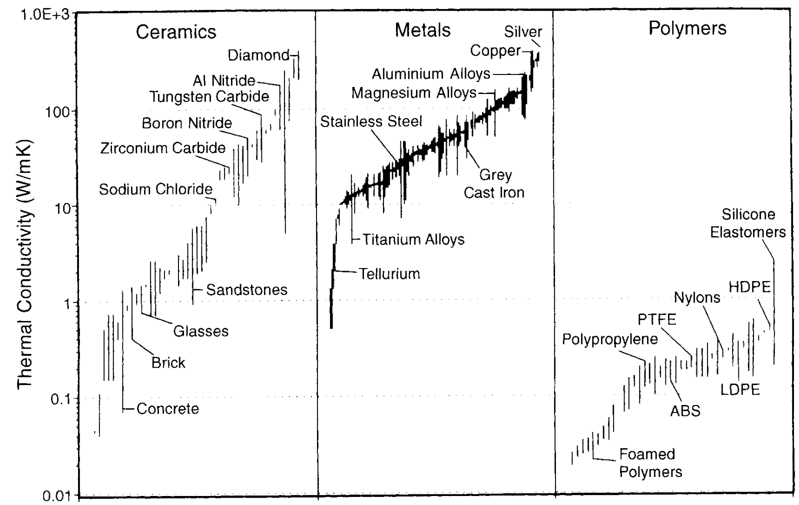
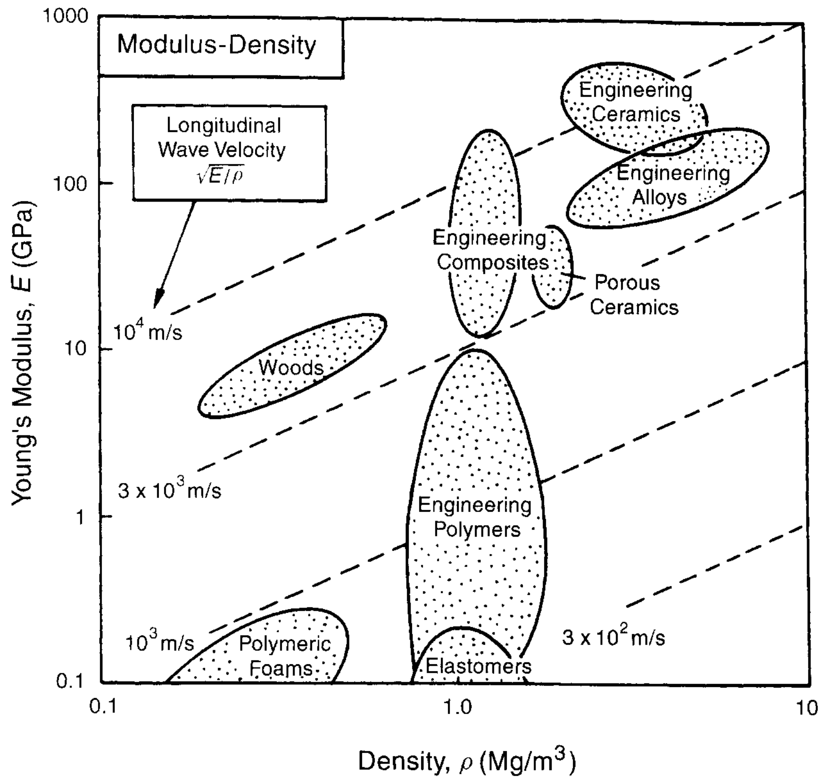
Material Property Chart



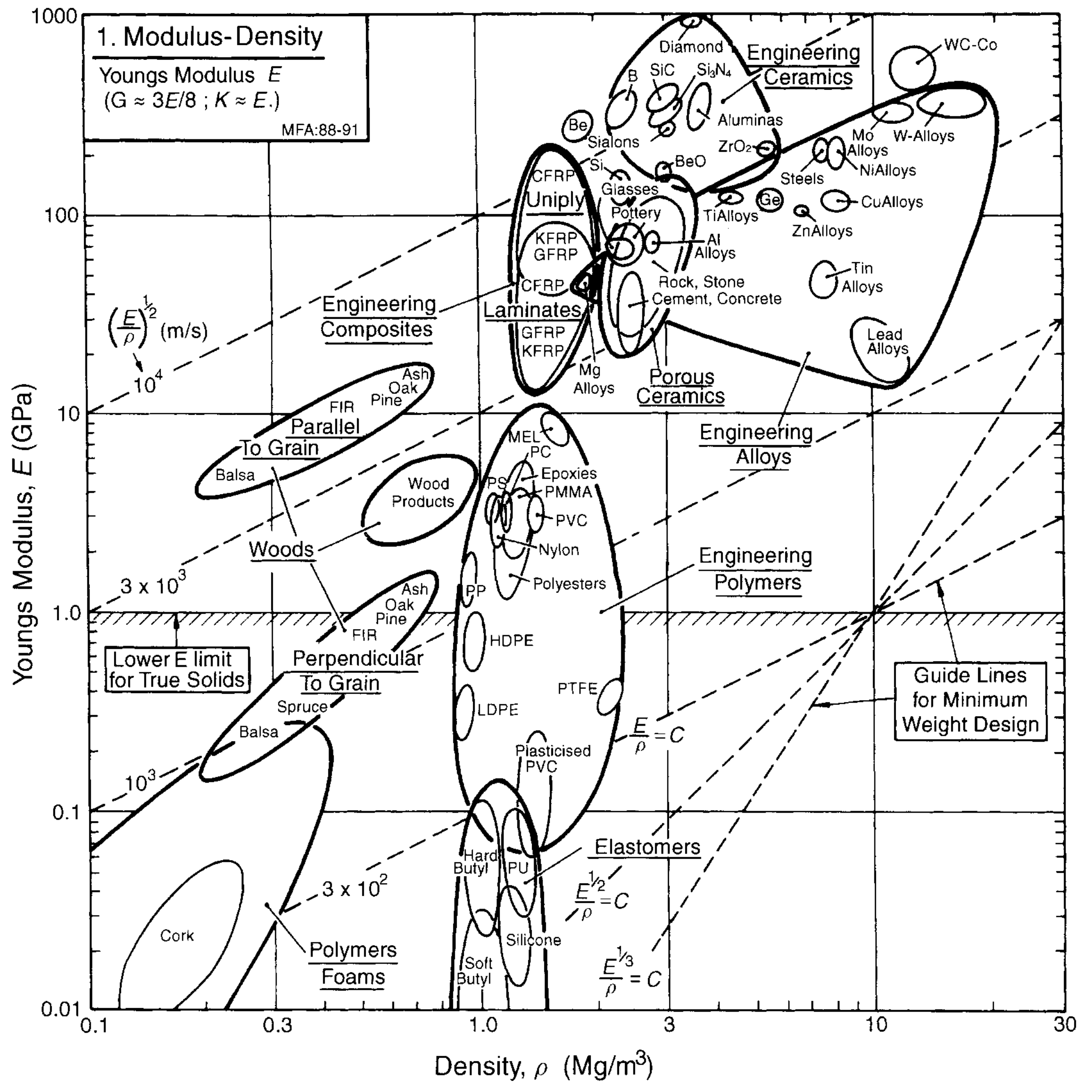


Property charts: Stiffness/weight



- Straight lines are the elastic wave speeds $\sqrt{\frac{E}{\rho}}$

Modulus to Density



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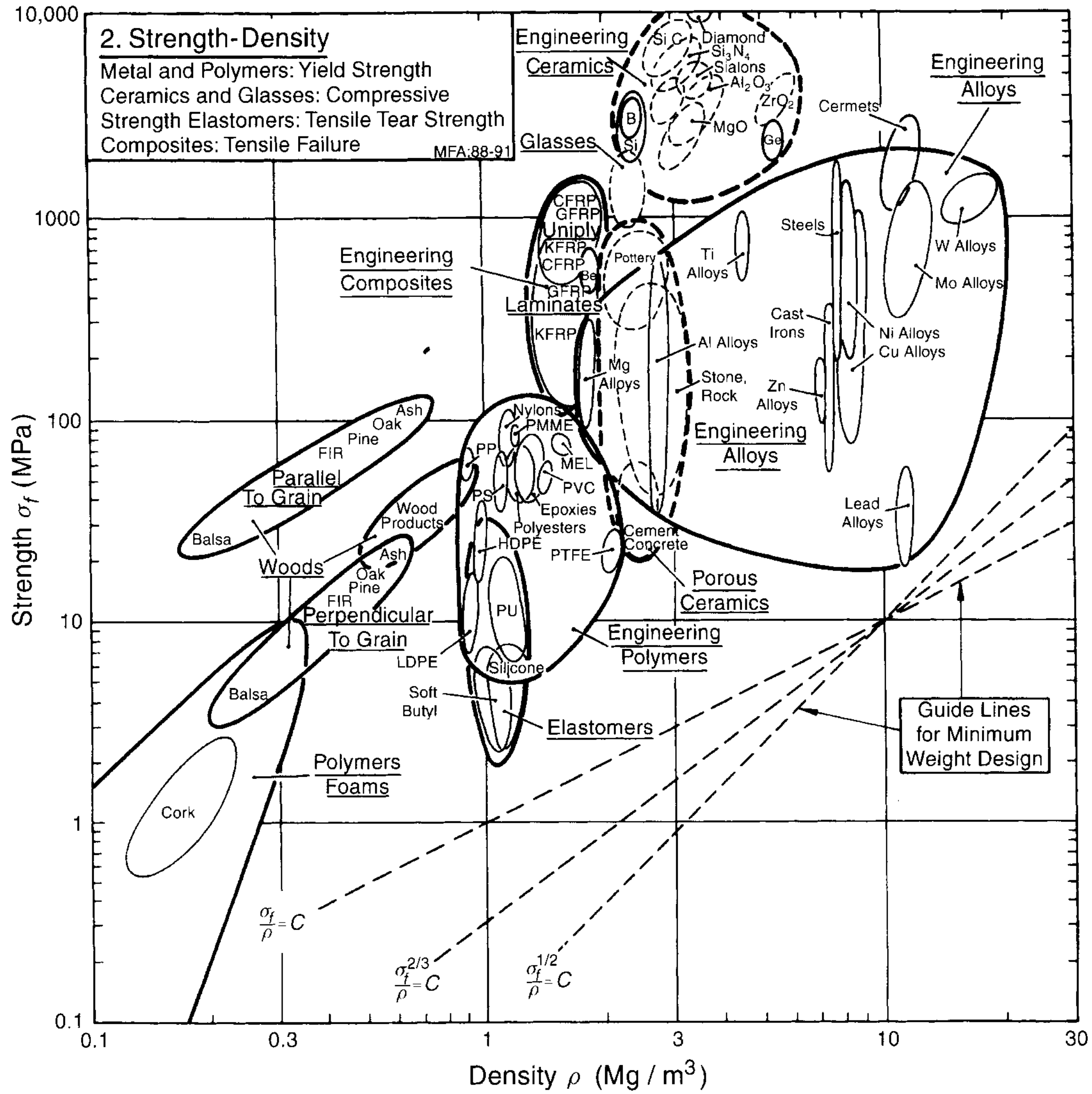
Strength to Density



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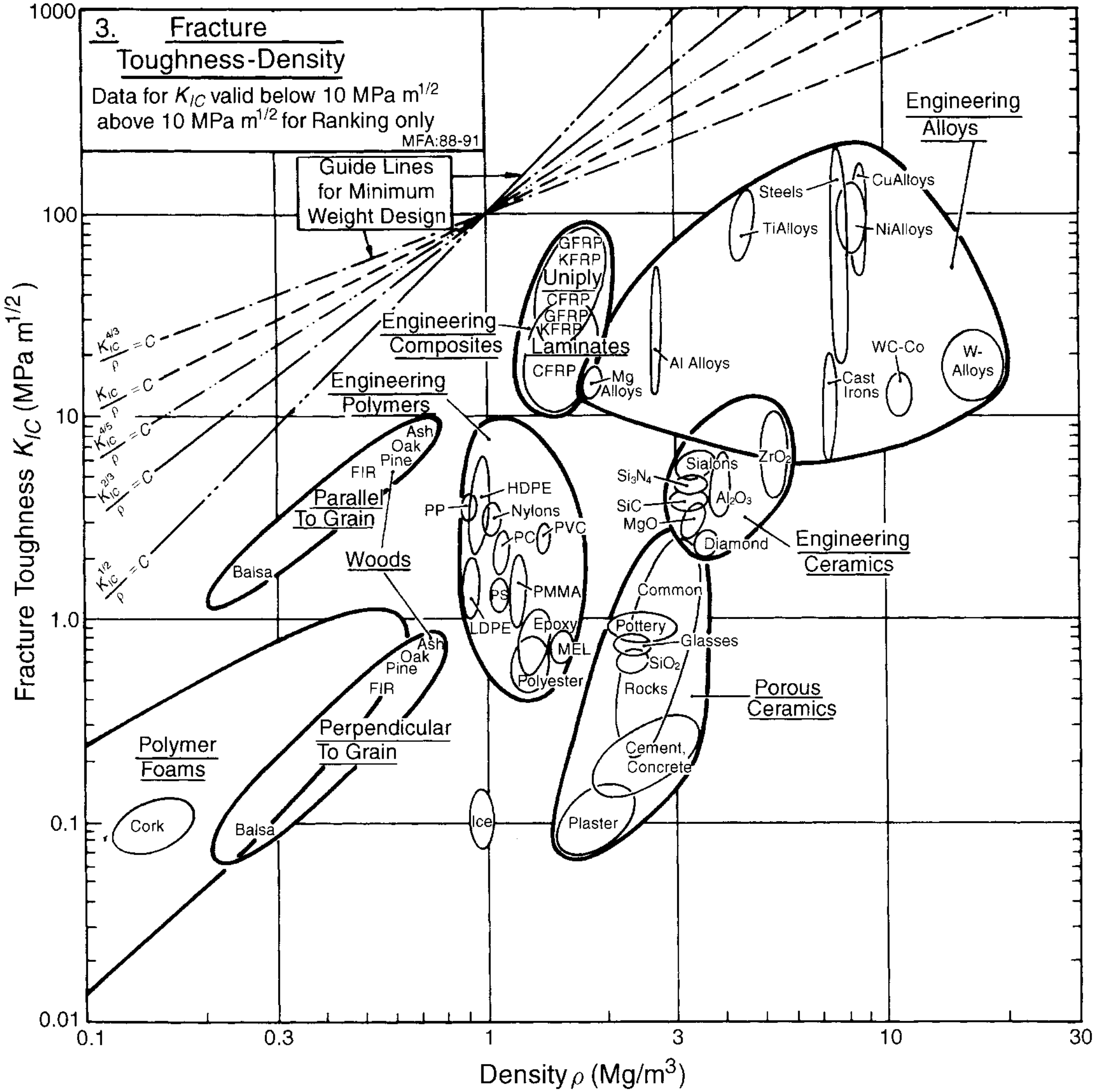
Fracture Toughness to Density



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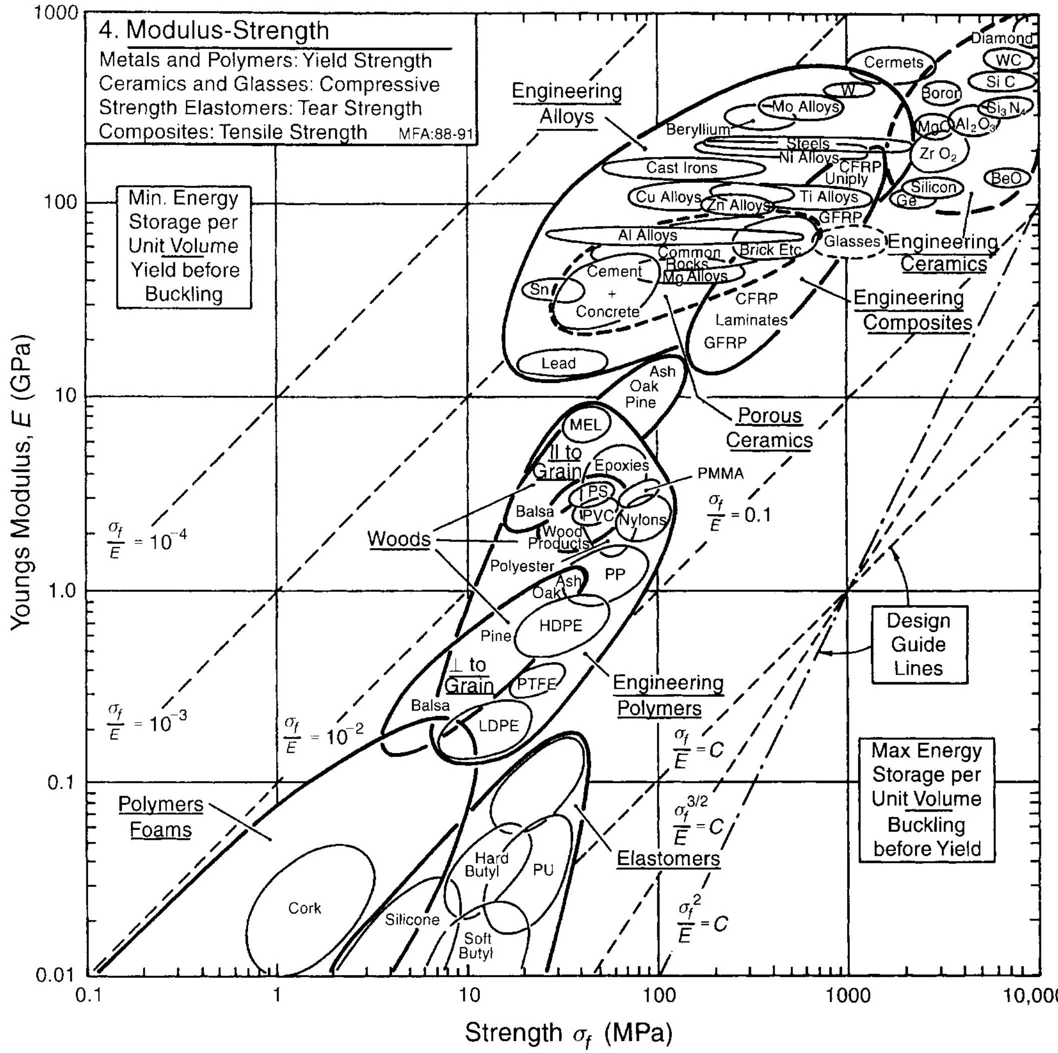
Modulus to Strength



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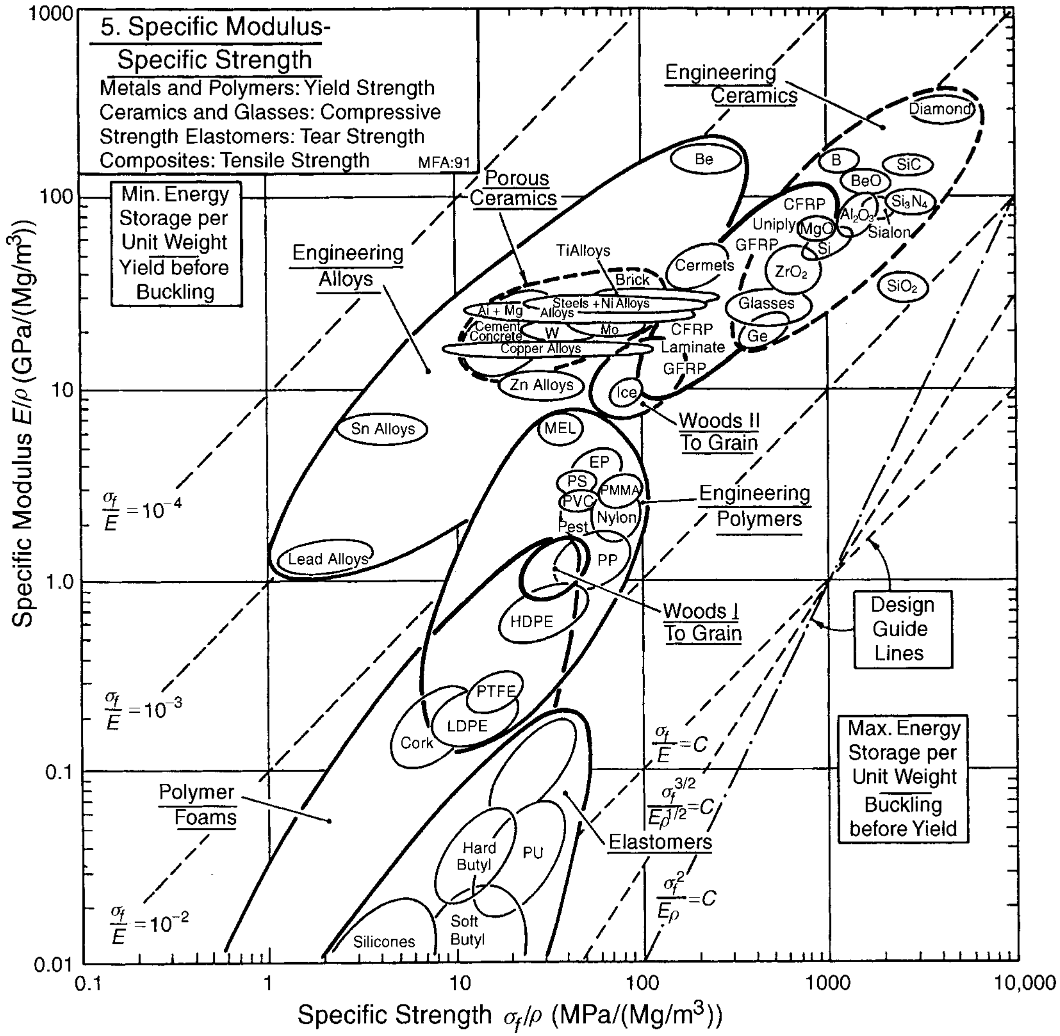
Specific Modulus to Specific Strength



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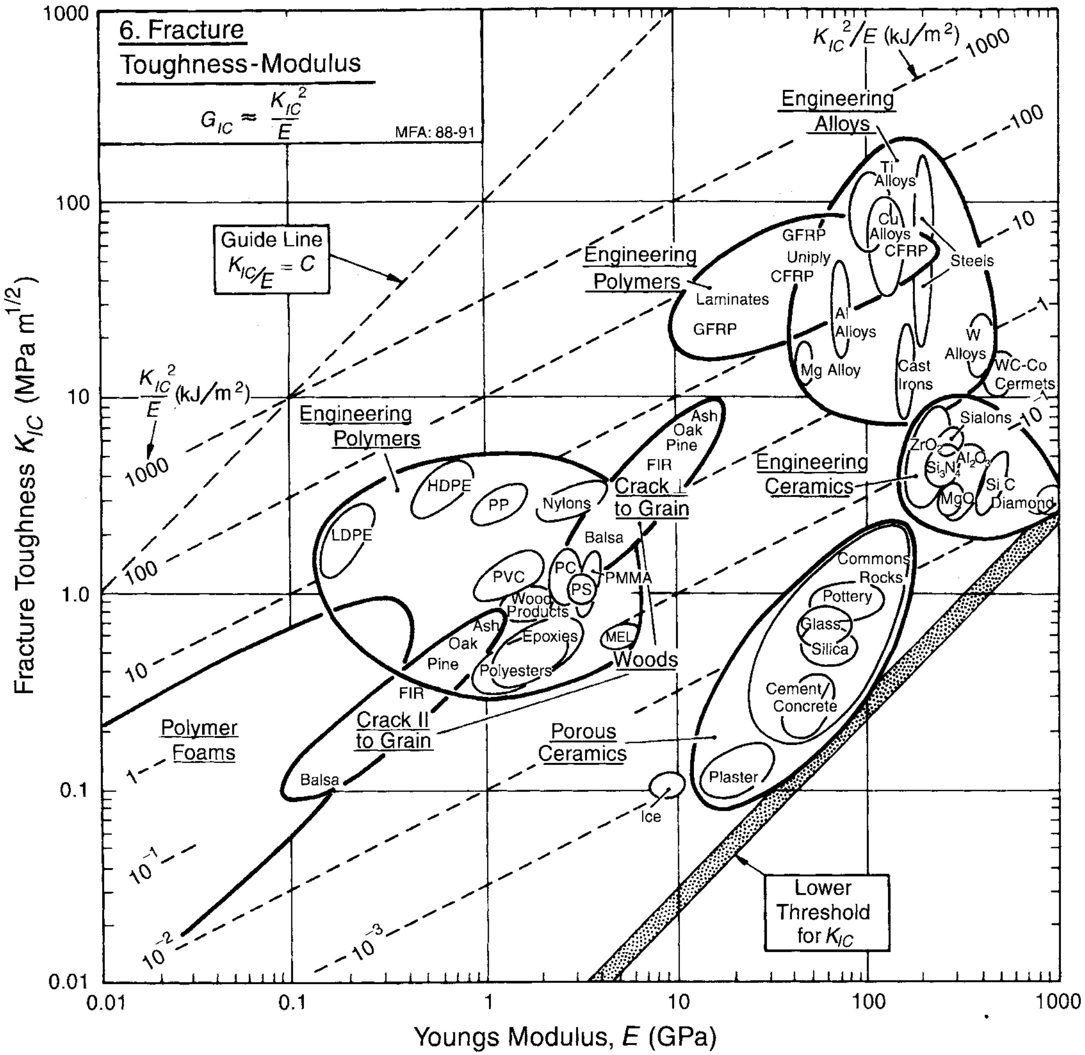
Fracture Toughness to Modulus



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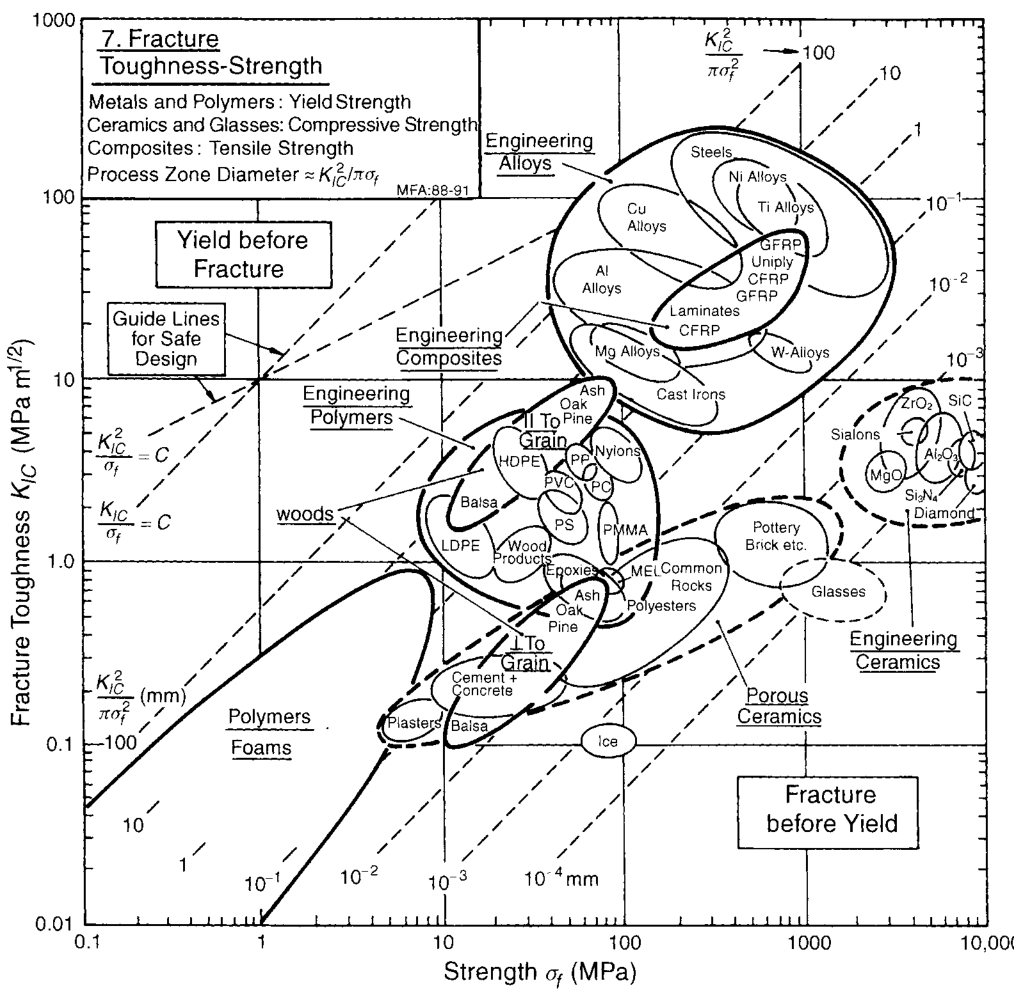
Fracture Toughness to Strength



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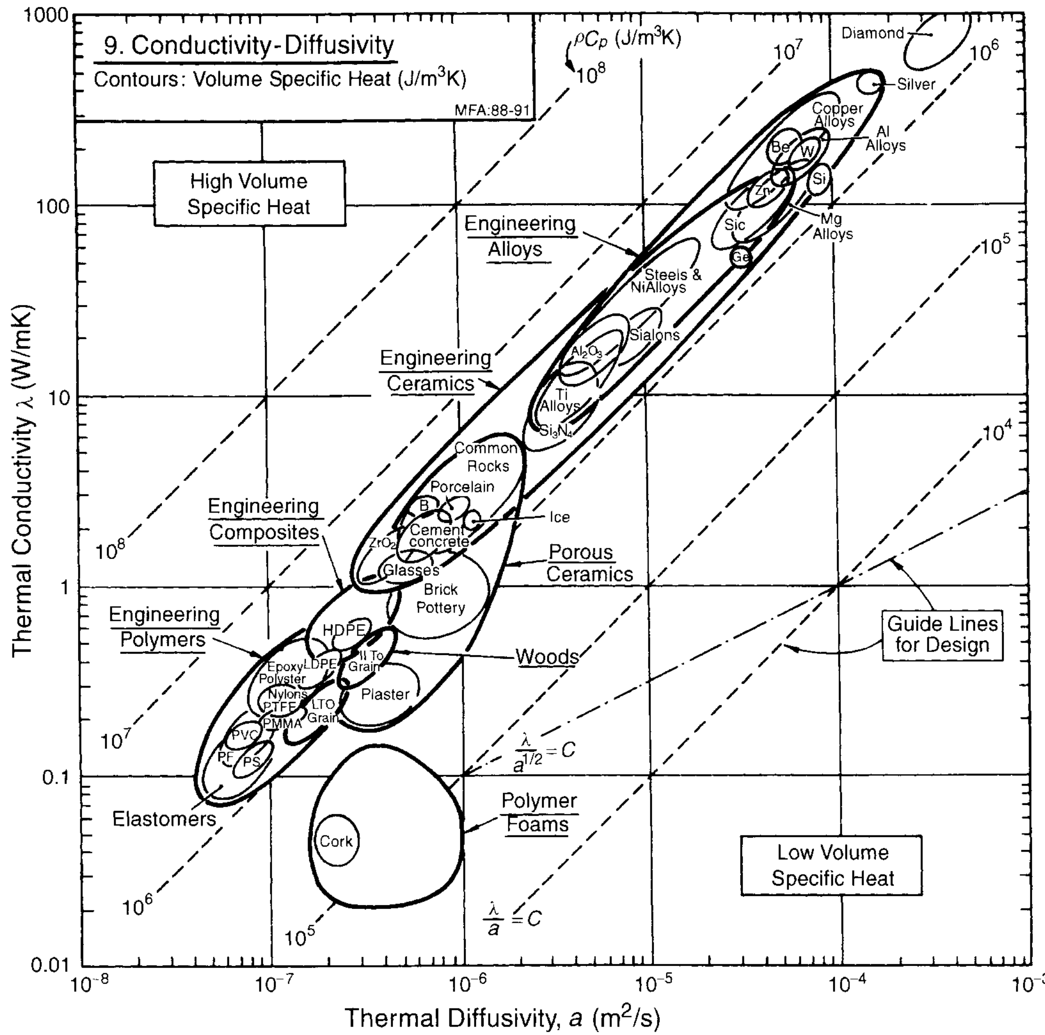
Thermal conductivity to diffusivity



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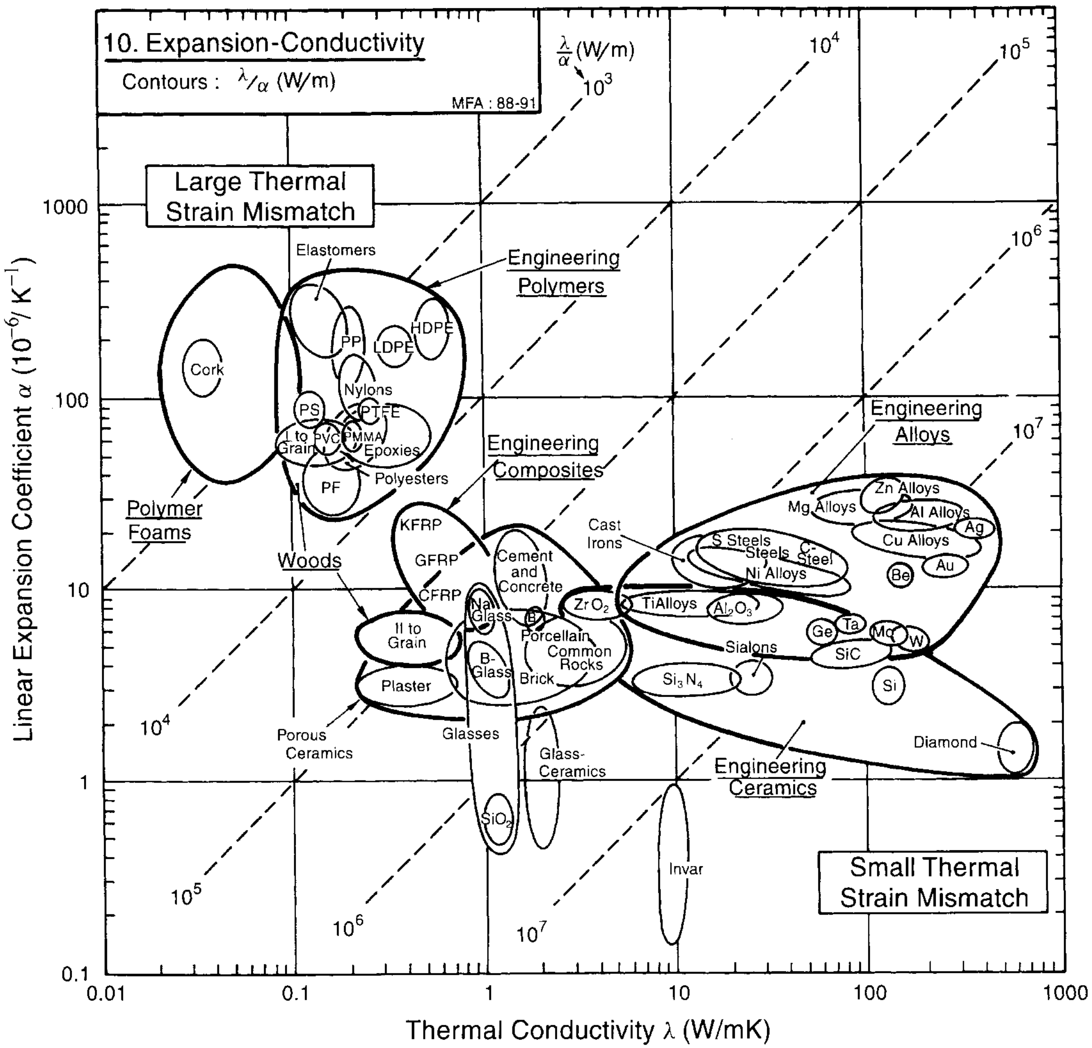
Expansion to conductivity



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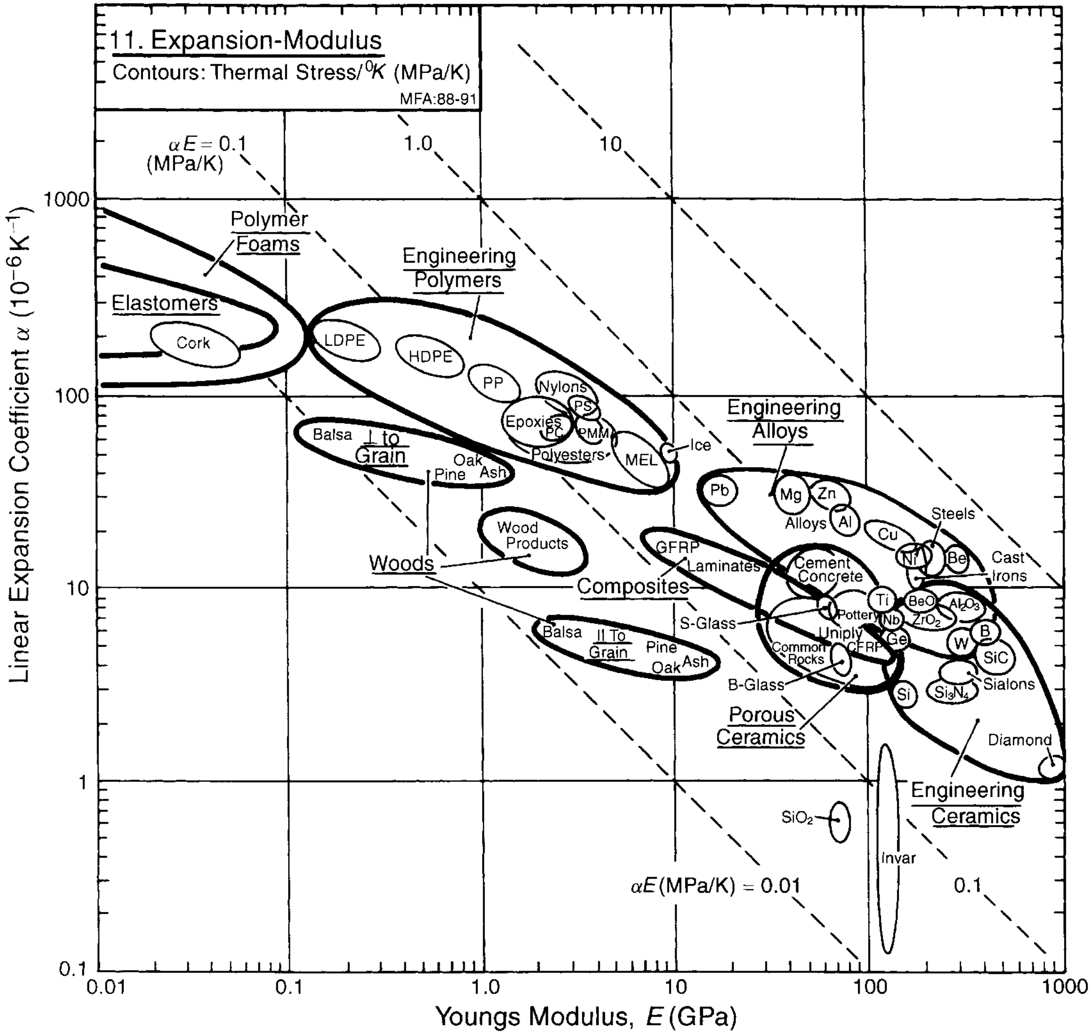
Expansion to Modulus



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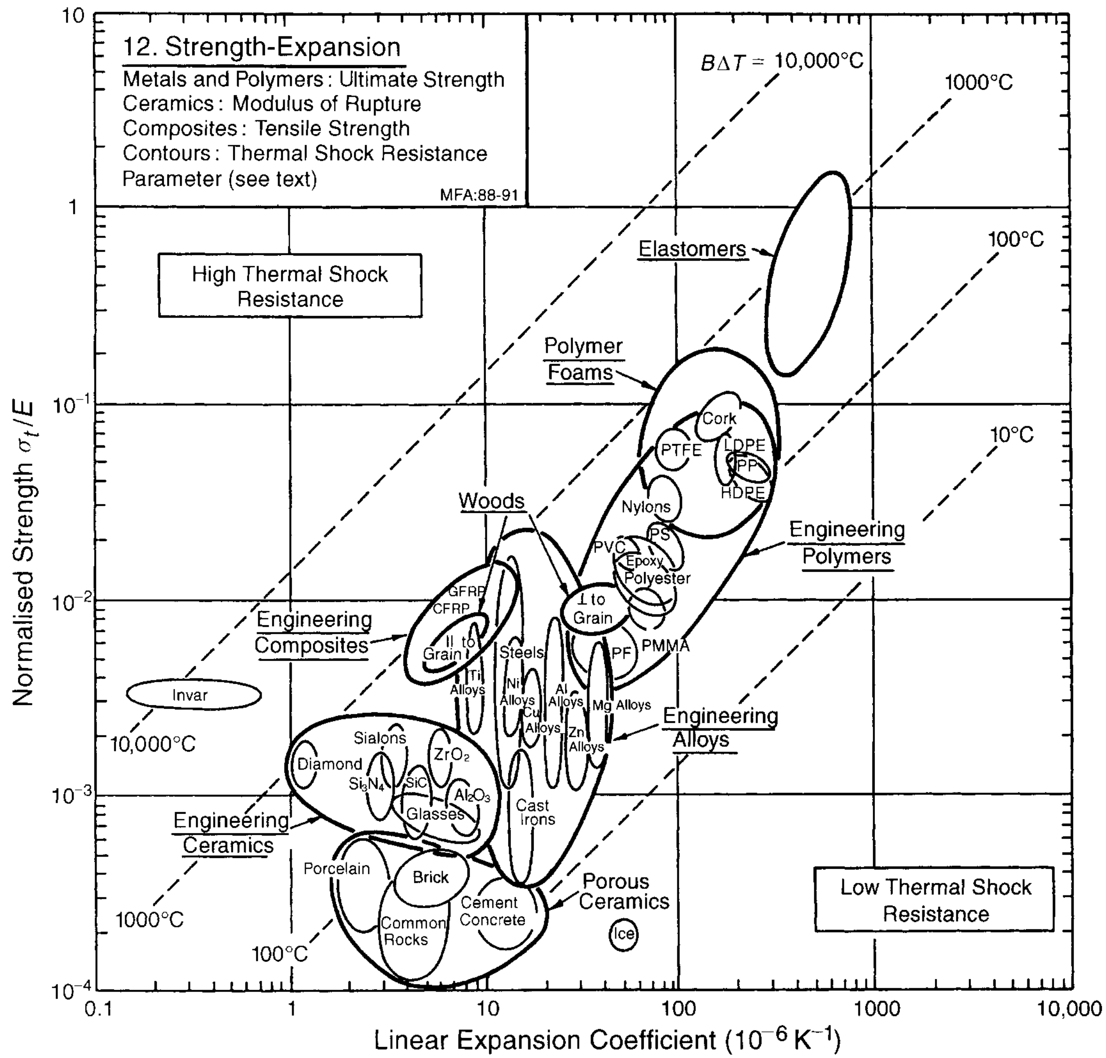
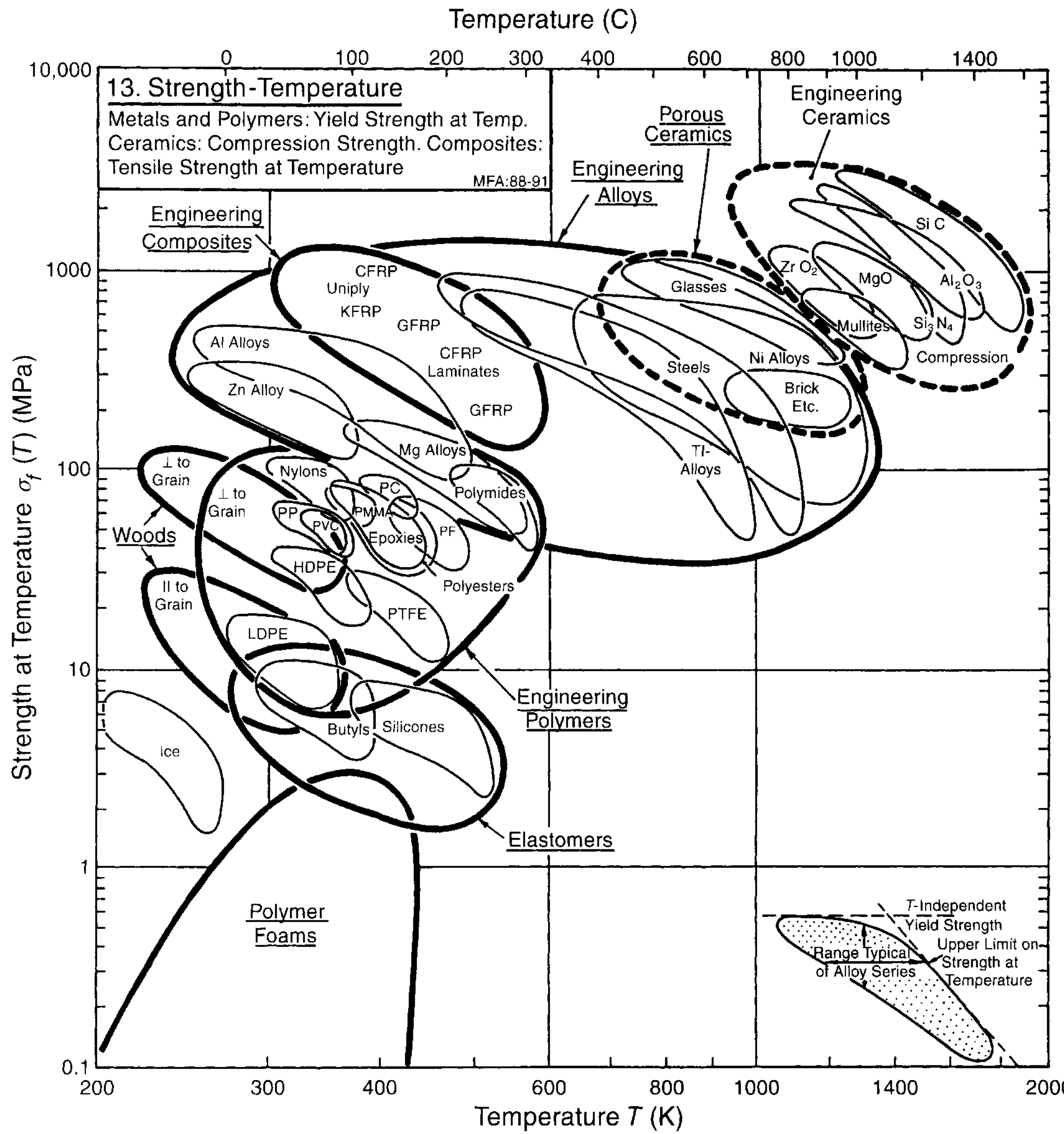
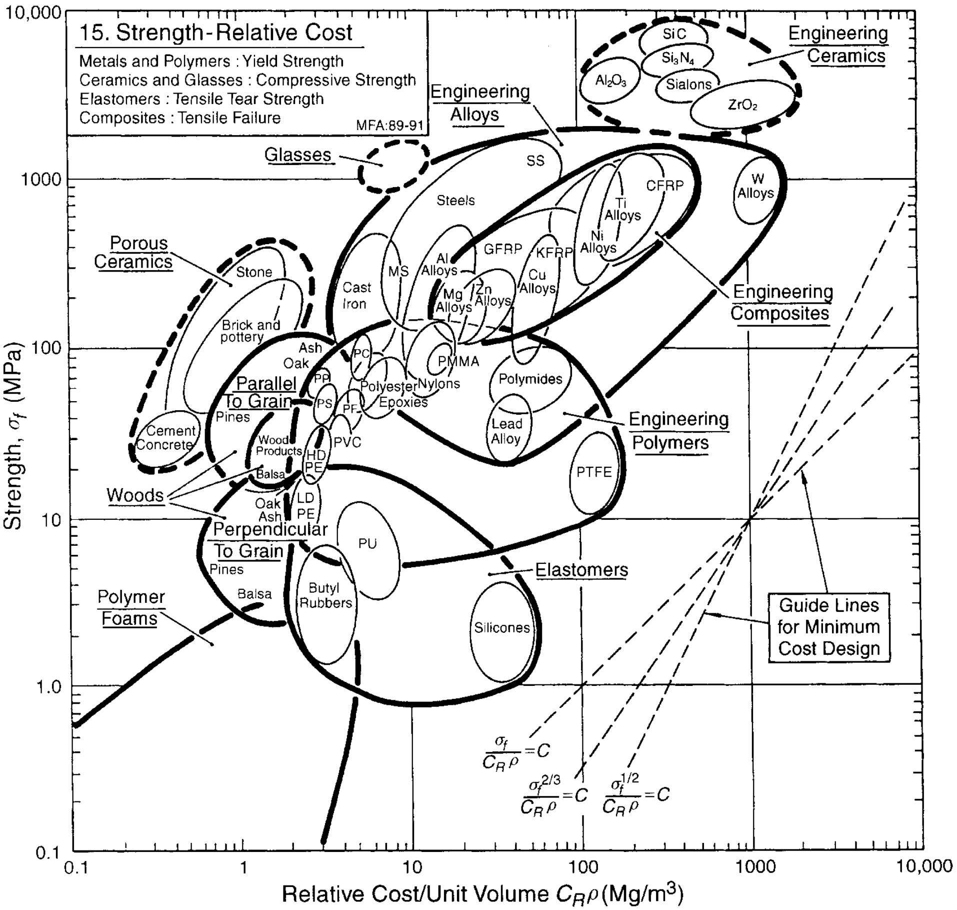
Normalized Strength to Expansion

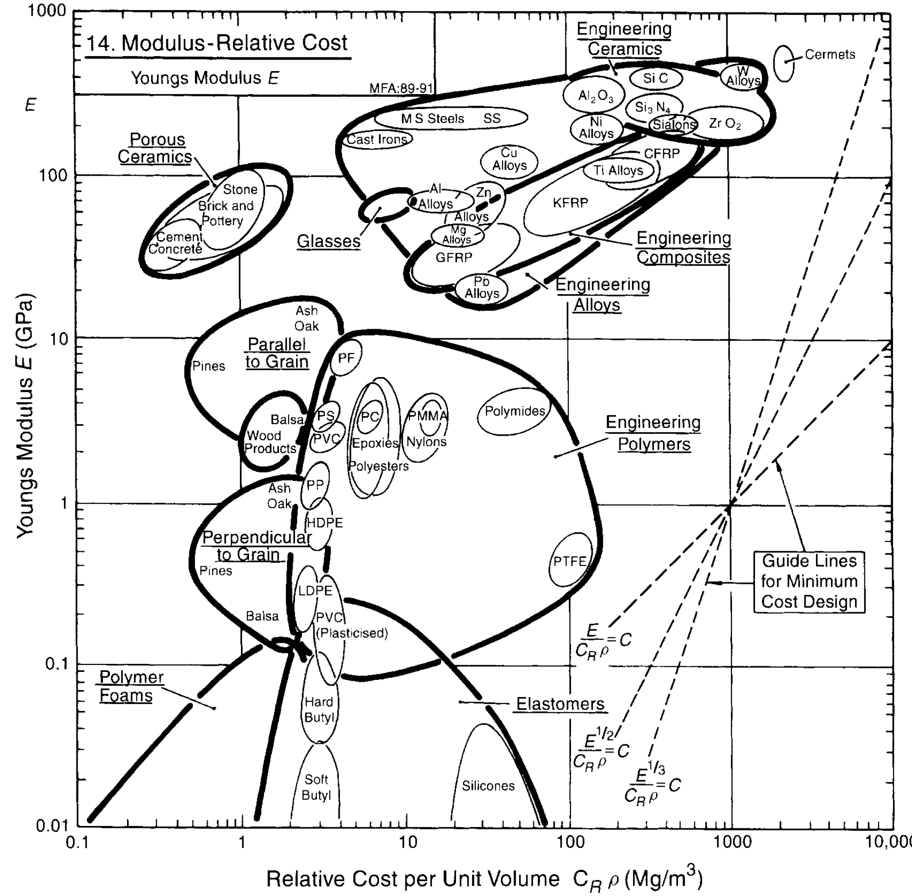


Strength at High Temperature

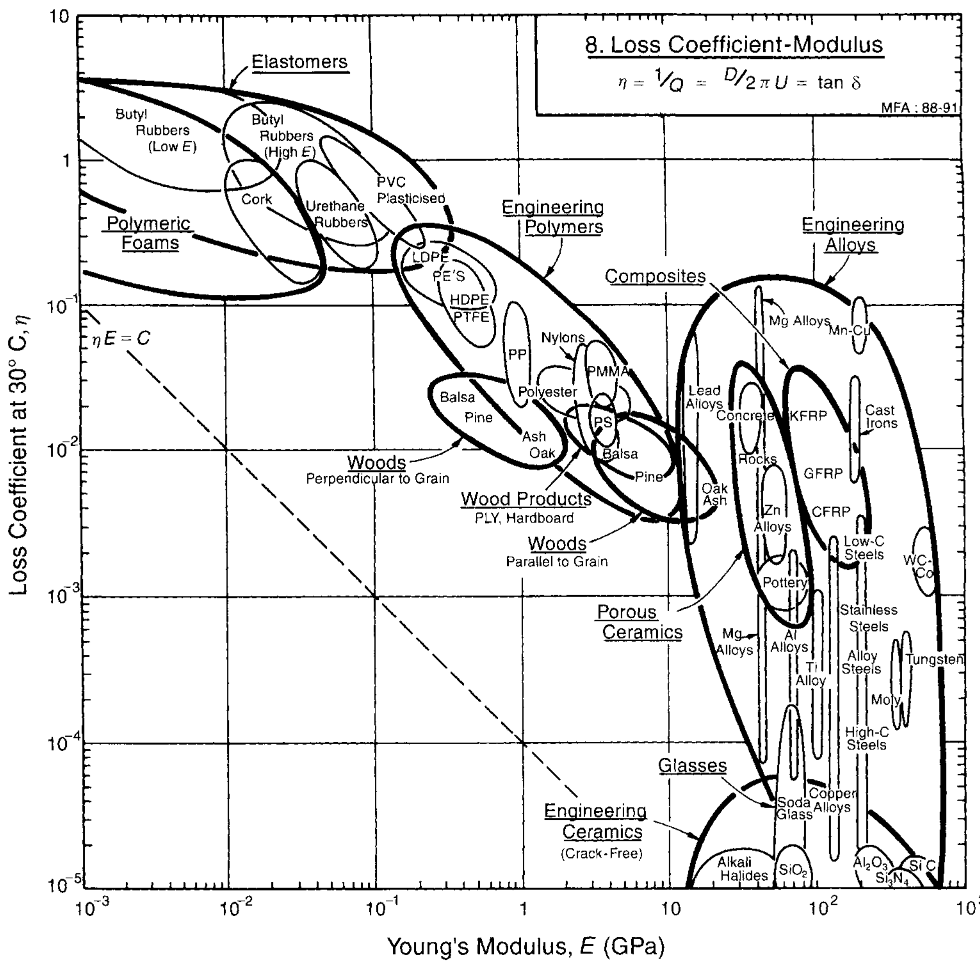


Relative Cost





Design for Impact



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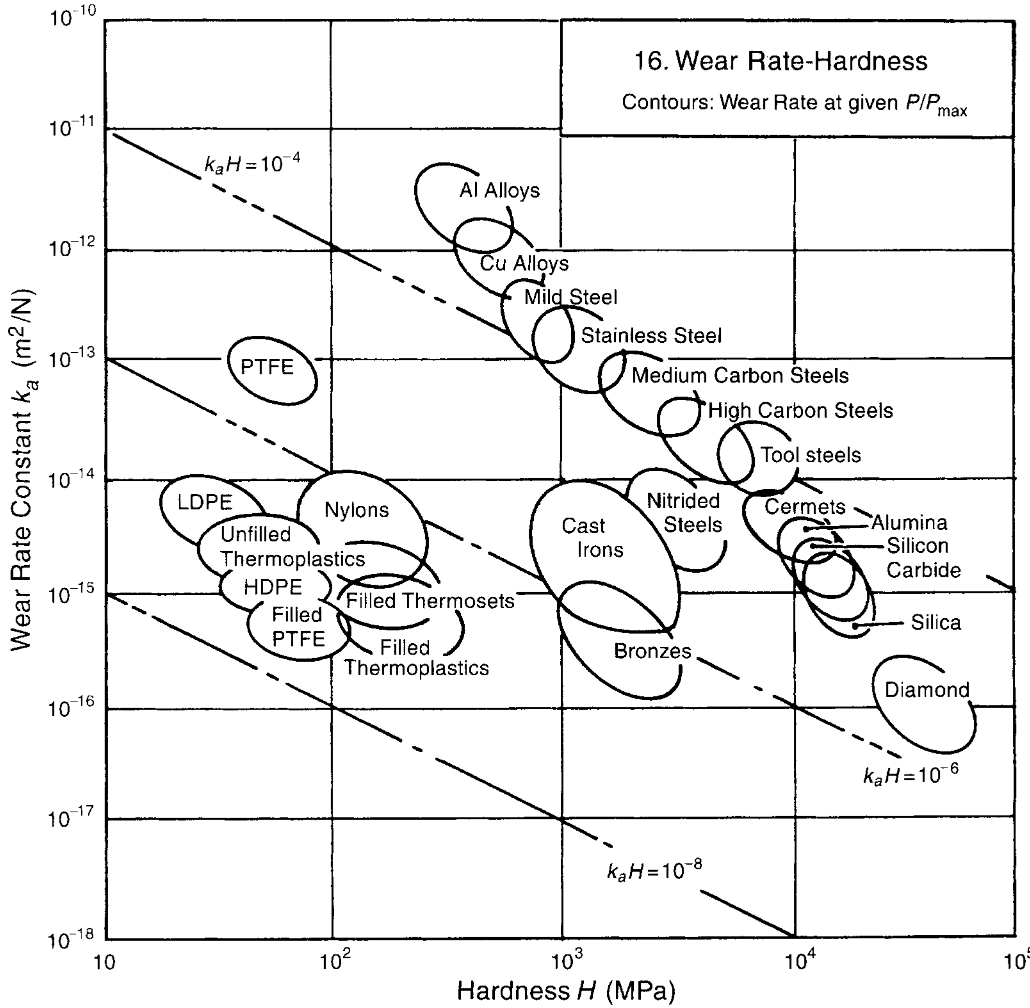
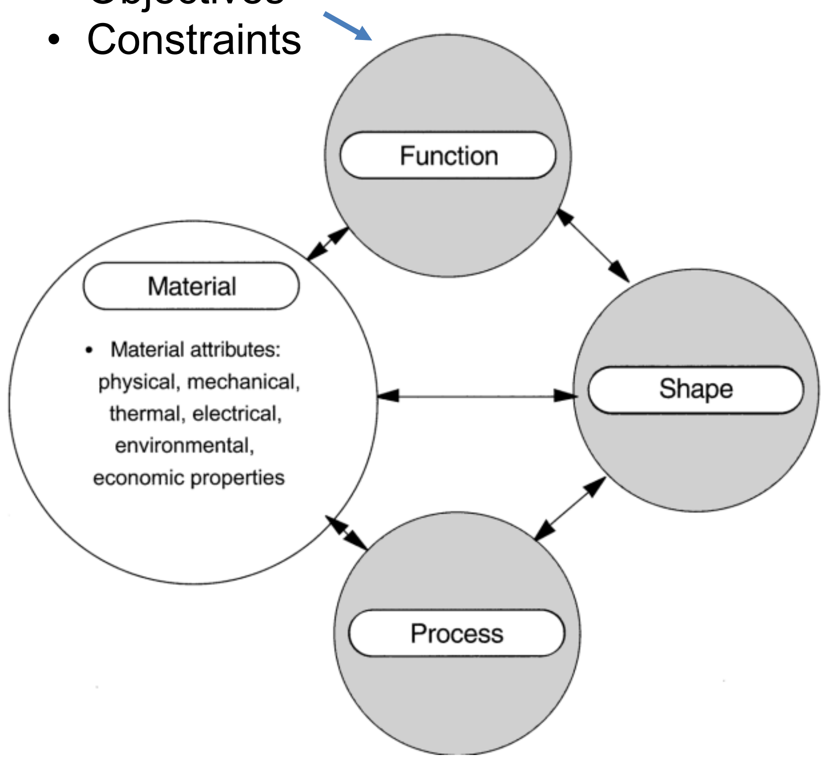
Wear Rate


16. Wear Rate-Hardness
Contours: Wear Rate at given P/P_{max}
$k_aH = 10^{-4}$
$k_aH = 10^{-6}$
$k_aH = 10^{-8}$
Al Alloys
Cu Alloys
Mild Steel
Stainless Steel
Medium Carbon Steels
High Carbon Steels
Tool steels
PTFE
LDPE
Nylons
Unfilled Thermoplastics
HDPE
Filled Thermosets
Filled PTFE
Filled Thermoplastics
Cast Irons
Nitrided Steels
Cermets
Alumina
Silicon Carbide
Silica
Bronzes
Diamond
Wear Rate Constant k_a (m^2/N)
Hardness H (MPa)
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10
10^2
10^3
10^4
10^5
(b)

Material Selection

- Identifying the desired attribute for objectives and constraints *(Translation)*
- Comparing with real engineering materials for the best match *(Screening and Ranking)*

Translation
- Objectives
- Constraints



Mapping Design Requirements to Materials

"Translation"

Design concept

Analyse: Function *What does the component do ?*

Objective(s) *What is to be maximised or minimised ?*

Constraints *What essential conditions must be met ?*

Free variables *Which design variables are free ?*

From which we obtain …

- **Screening criteria** expressed as numerical limits on material property-values
  Or expressed as requirements for processing, corrosion, ….

- **Ranking criteria** based on material indices that characterise performance

Screening by Attributes and Links

Screen on attributes

Example: heat exchanger tubes

Requirements: must
- operate at 100°C
- be electrical insulator
- conduct heat well

→

Retain materials with:
- max operating temp > 100C
- resistivity R > 10^{20} $\mu\Omega$.cm
- T-conduct. λ > 100 W/m.K

Screen on links

Example: cheap metal window frame

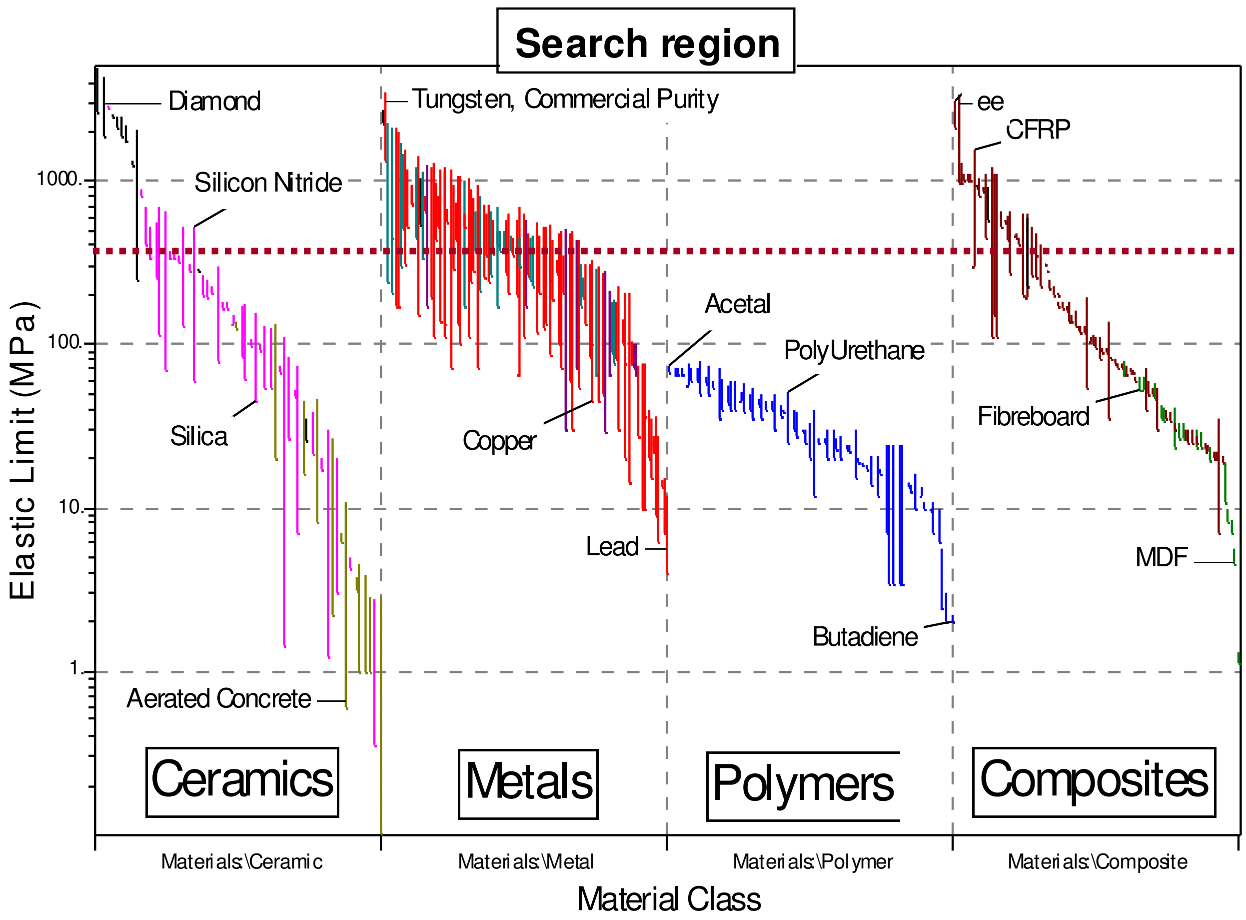
Requirements: must
- be extrudable

→

Retain materials with:
- links to "extrusion"

Screen on both attributes and links

Screening on Attributes



Ranking by Performance

- Objective: Metric of performance which can be maximized or minimized, such as mass, volume, cost per unit attribute

Performance metrics:
Minimise --

- Cost per unit strength

$$P \propto \frac{C_m}{\sigma_y}$$

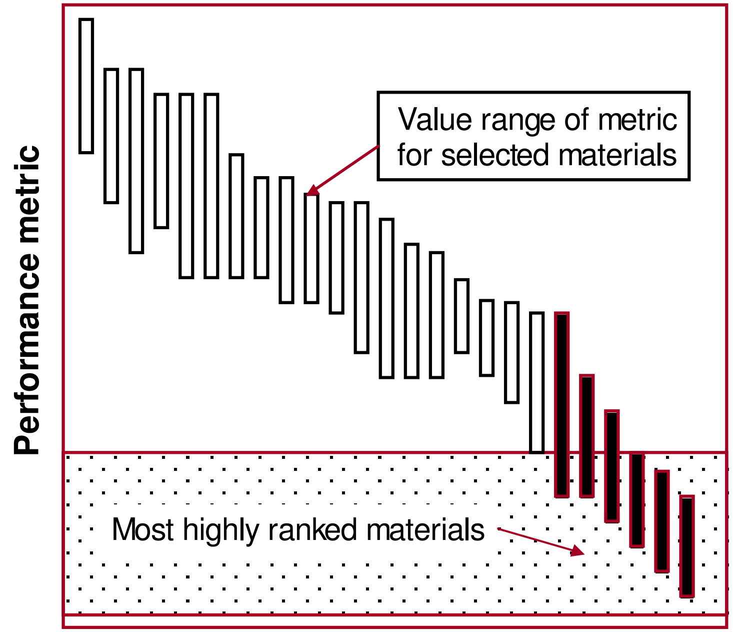
- Mass per unit bending stiffness

$$P \propto \frac{\rho}{E^{1/2}}$$

- Volume per unit energy absorbed

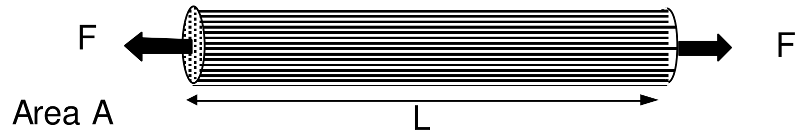
$$P \propto \frac{1}{\sigma_y \varepsilon_D}$$

- Many more ....



Material Indices: Tie Rod

- Minimizing mass for a light strong tie rod



Function *Tie-rod*

Constraints *Length L is specified*
Must not fail under load F

Objective *Minimise mass m*

Free variable *Cross-section area A is free*

- Objective

$Minimize\ m = AL\rho$ where L is length, A is cross-sectional area and ρ is density

- Constraint: $\frac{F^*}{A} \leq \sigma_f$ where F* is the force and σ_f is the failure strength

$$m \geq (F^*)(L)\left(\frac{\rho}{\sigma_f}\right)$$

Material Properties

Functional Constraint

Geometric Constraint

Minimize this material index or $\frac{\sigma_f}{\rho}$ specific strength can be maximized

For stiffest tie choose high $\frac{E}{\rho}$

Light Stiff Panel

- Function: Panel
- Objective: Minimize m of the panel
- Constraints: Bending Stiffness, S* (functional constraint)

  Length L and width b specified (geometric constraint)
- Free Variables: Panel thickness h and material

$$m = AL\rho = bhL\rho$$

The bending stiffness S can be given by, $S = \frac{C_1 EI}{L^3} \geq S^* \ and \ I = \frac{bh^3}{12}$

$$m = hbL\rho = \left(\frac{12L^3S^*}{C_1Eb}\right)^{\frac{1}{3}} bL\rho = \left(\frac{12S^*}{C_1b}\right)^{\frac{1}{3}} (bL^2)\left(\frac{\rho}{E^{\frac{1}{3}}}\right)$$

→ Material Properties

$Mp = \frac{E^{\frac{1}{3}}}{\rho}$ (For stiffness); $Mp = \frac{\sigma y^{\frac{1}{2}}}{\rho}$ (For strength)

Light Stiff Beam

- Function: Beam
- Objective: Minimize m of the panel
- Constraints: Bending Stiffness, S* (functional constraint)

  square cross-section (geometric constraint)
- Free Variables: Area A and material

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

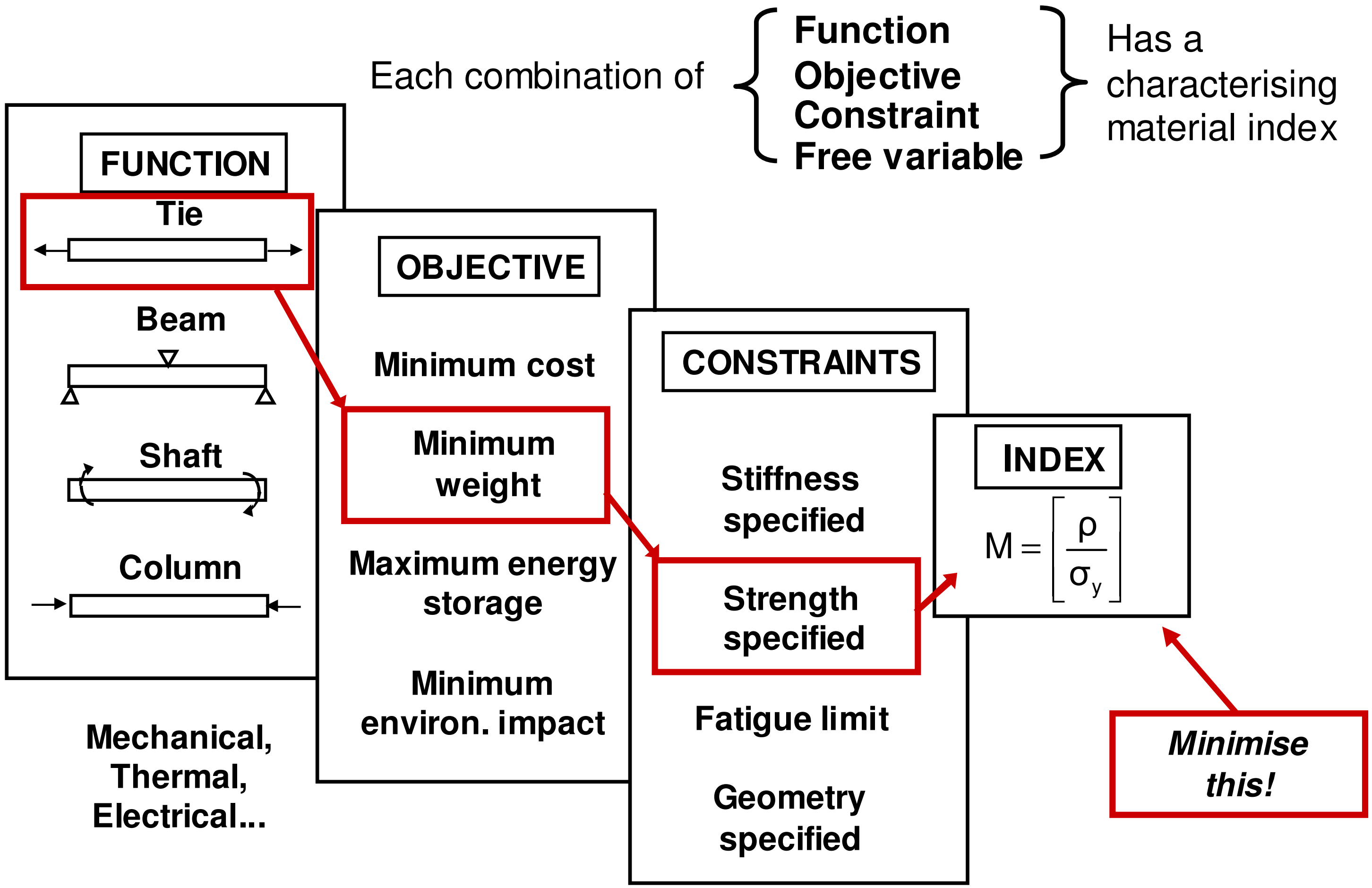
The bending stiffness S can be given by, $S = \frac{C_2 EI}{L^3} \geq S^* \; and \; I = \frac{b^4}{12} = \frac{A^2}{12}$

$$m = AL\rho = \left(\frac{12L^3S^*}{C_1E}\right)^{\frac{1}{2}} L\rho = \left(\frac{12L^3S^*}{C_2}\right)^{\frac{1}{2}} (L)\left(\frac{\rho}{E^{\frac{1}{2}}}\right)$$

→ Material Properties

$Mp = \frac{E^{\frac{1}{2}}}{\rho}$ (For stiffness); $Mp = \frac{\sigma y^{\frac{2}{3}}}{\rho}$ (For strength)

Ashby's Methodology



Material Indices

Material properties --

the "Physicists" view of materials, e.g.

Cost,	C_m
Density,	ρ
Modulus,	E
Strength,	σ_y
Endurance limit,	σ_e
Thermal conductivity,	λ
T- expansion coefficient,	α

Material indices --

the "Engineers" view of materials

Objective: minimise mass

Function	**Stiffness**	**Strength**
Tension (tie)	ρ/E	ρ/σ_y
Bending (beam)	$\rho/E^{1/2}$	$\rho/\sigma_y^{2/3}$
Bending (panel)	$\rho/E^{1/3}$	$\rho/\sigma_y^{1/2}$

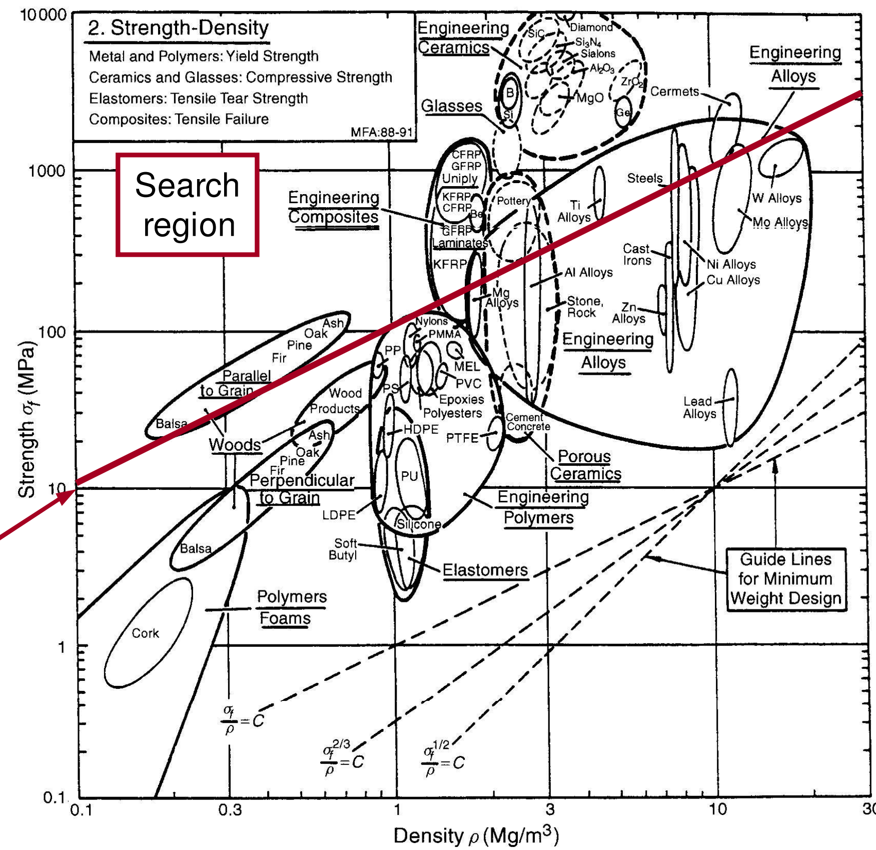
Minimise these!

Selection Using Charts

$$C = \frac{\rho}{\sigma_y}$$

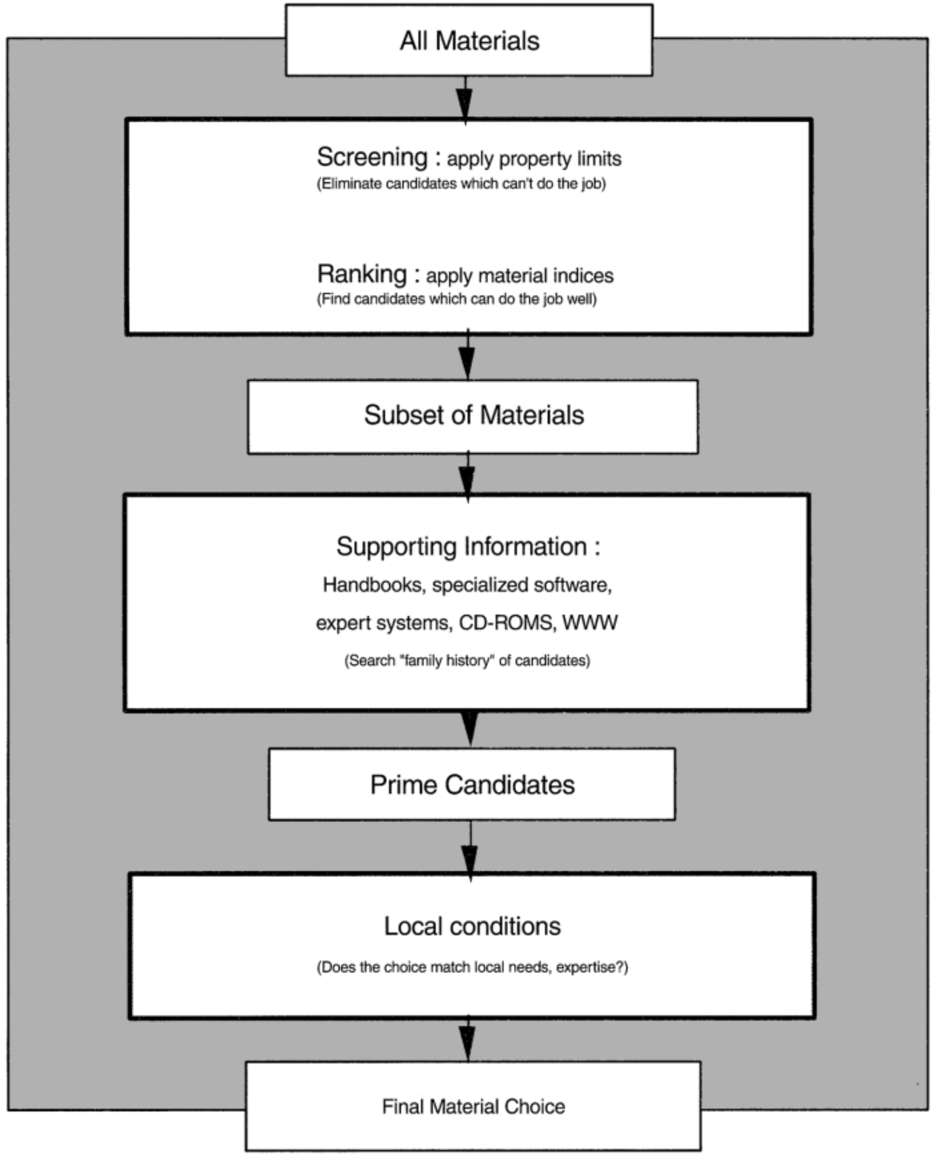
$$\Rightarrow \quad \sigma_y = \rho / C$$

$$\text{Log}(\sigma_y) = \text{Log}(\rho) - \text{Log}(C)$$

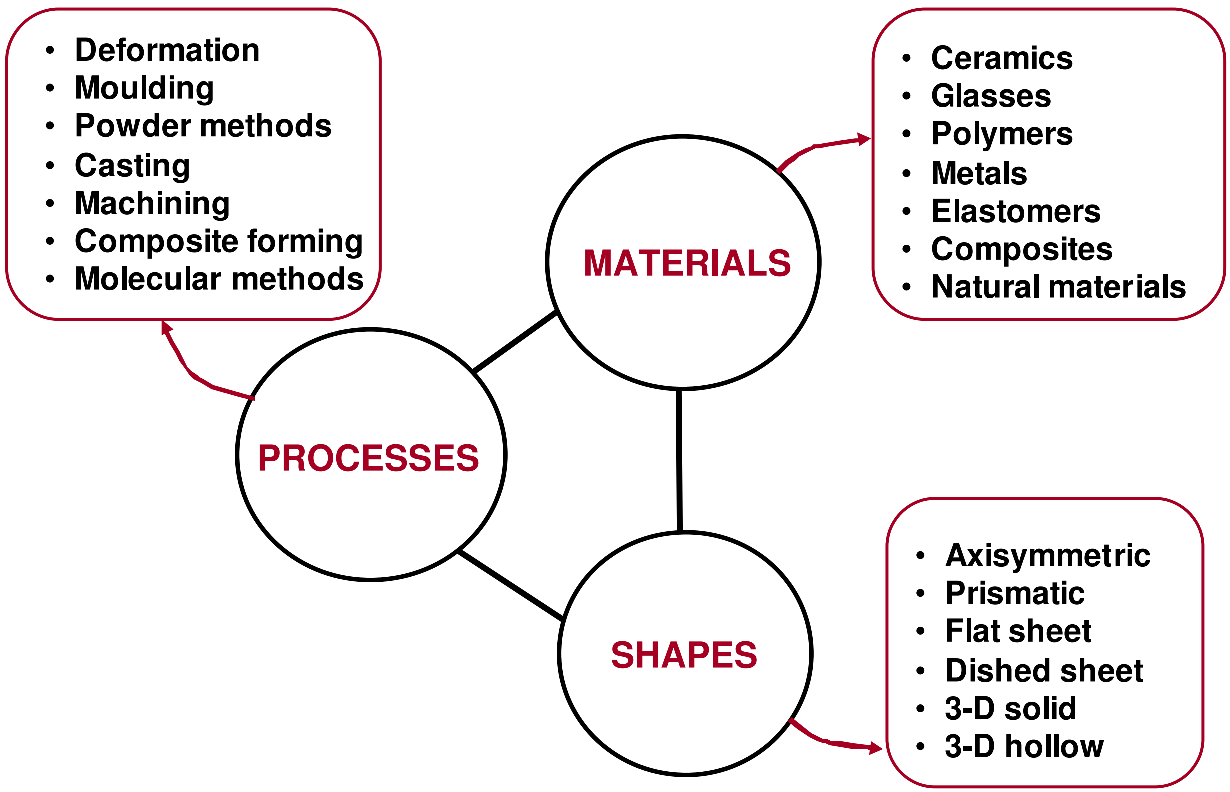


$$\frac{\rho}{\sigma_y} = C$$

Contours of constant C are lines of slope 1 on an σ_y-ρ chart


All Materials
Screening : apply property limits
(Eliminate candidates which can't do the job)
Ranking : apply material indices
(Find candidates which can do the job well)
Subset of Materials
Supporting Information :
Handbooks, specialized software,
expert systems, CD-ROMS, WWW
(Search "family history" of candidates)
Prime Candidates
Local conditions
(Does the choice match local needs, expertise?)
Final Material Choice

Materials, Shapes and Processes



Process Material Compatibility

Material Class

Process Class		Metals					Ceramics & Glasses				Polymers & Elastomers			Composites		
		Ferrous	Refractory	Precious	Heavy	Light	Cementitous	Vitreous	Fine	Glasses	Thermosets	Thermoplastics	Elastomers	PMCs	MMCs	CMCs
Casting	Gravity	2	1	2	2	2	0	0	0	1	0	0	0	0	0	0
	Low pressure	2	0	2	2	2	0	0	0	2	0	0	0	0	1	0
	High pressure	1	0	2	2	2	0	0	0	1	0	0	0	0	2	0
	Investment	2	2	2	2	2	0	0	0	0	0	0	0	0	0	0
Moulding	Injection	0	0	2	0	0	0	0	0	2	2	2	2	2	0	0
	Compress	0	0	2	0	0	0	0	0	2	2	2	2	2	1	0
	Blow	0	0	0	0	0	0	0	0	2	0	2	0	0	0	0
	Foam	0	0	0	0	0	0	0	0	0	2	2	2	0	0	0
Deformation	Cold	2	0	2	2	2	0	0	0	0	0	0	0	0	0	0
	Warm	2	0	2	2	2	0	0	0	0	0	0	0	0	0	0
	Hot	2	2	2	2	2	0	0	0	2	0	0	0	0	0	0
	Sheet	2	1	2	2	2	0	0	0	0	0	2	0	0	1	0
Machining	Turn	2	2	2	2	2	0	1	0	0	2	2	0	2	2	0
	Mill	2	2	2	2	2	0	1	0	0	2	2	0	2	2	0
	Grind	2	2	1	2	2	0	2	2	2	0	0	0	0	2	2
	Polish	2	2	2	2	2	0	2	2	2	0	0	0	0	1	2
Powder Methods	Sinter/HIP	2	2	2	2	2	0	2	2	1	0	2	0	0	2	2
	Slip cast	0	0	0	0	0	0	2	2	1	0	0	0	0	0	1
	Spray forming	2	2	2	2	2	0	2	2	2	2	2	0	2	0	0
	Hydration	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Composite Forming	Lay-up	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2
	Mould	0	0	0	0	0	0	0	0	0	2	2	2	2	0	0
	Squeeze-cast	1	0	0	2	2	0	0	0	0	0	0	0	0	2	0
	Filament wind	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
Molecular Methods	PVD	0	2	2	2	0	0	0	2	.0	0	0	0	0	1	0
	CVD	0	2	2	2	0	0	0	2	0	0	0	0	0	1	2
	Sputtering	2	2	2	2	2	0	0	0	0	0	0	0	0	0	0
	Electroforming	1	0	2	2	0	0	0	0	0	0	0	0	0	0	0
Special Methods	Electrochemical	2	2	2	2	2	0	0	0	0	0	0	0	0	2	0
	Ultrasonic	1	2	0	0	0	0	2	2	2	0	0	0	0	0	2
	Chemical	2	2	2	2	2	0	2	2	2	0	0	0	0	0	0
	Thermal Beam	2	2	2	2	2	0	2	2	2	2	2	2	2	2	2
Fabrication	Weld/braze	2	2	2	2	2	0	0	0	0	0	2	0	0	0	0
	Adhesive	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	Fasten	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	Microfabrication	2	2	2	2	2	0	2	2	2	2	2	2	2	2	2

spread of

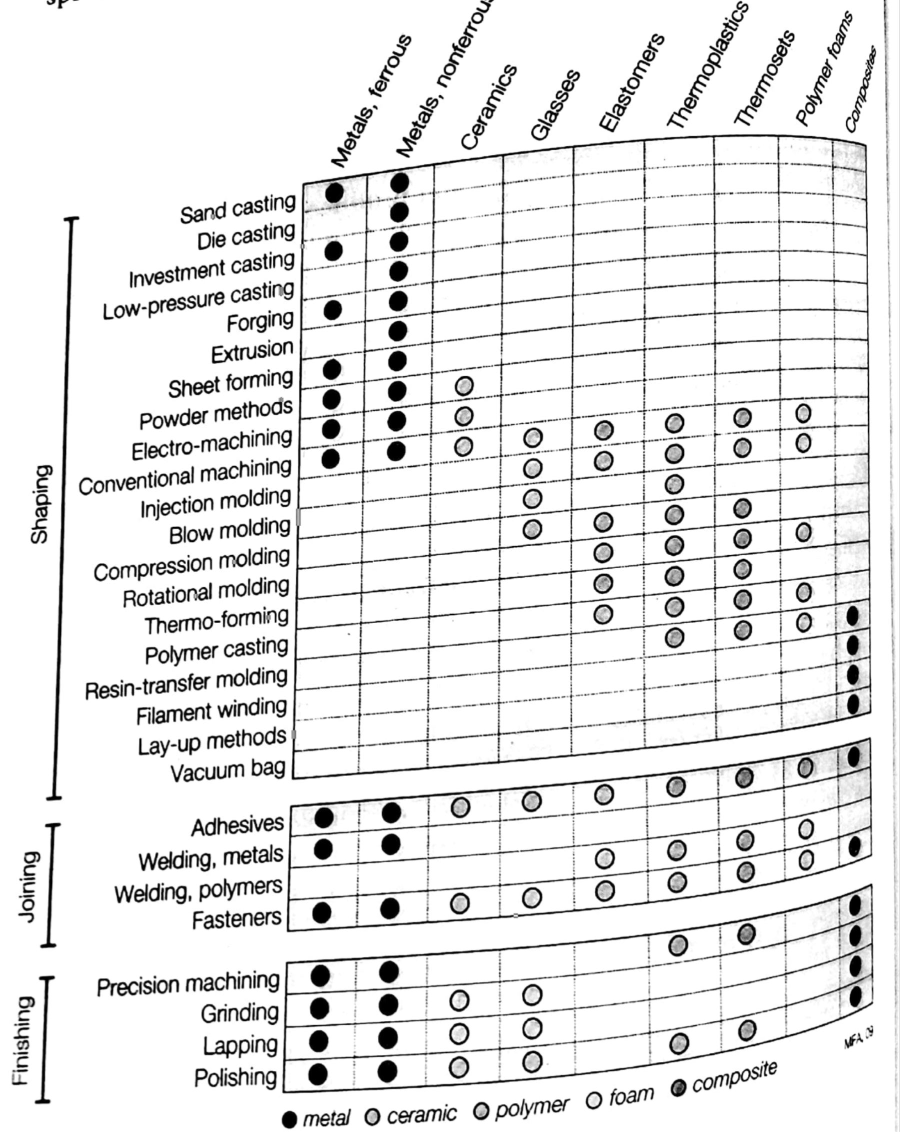


FIGURE 13.22

The process-material matrix. A colored dot indicates that the pair are compatible.

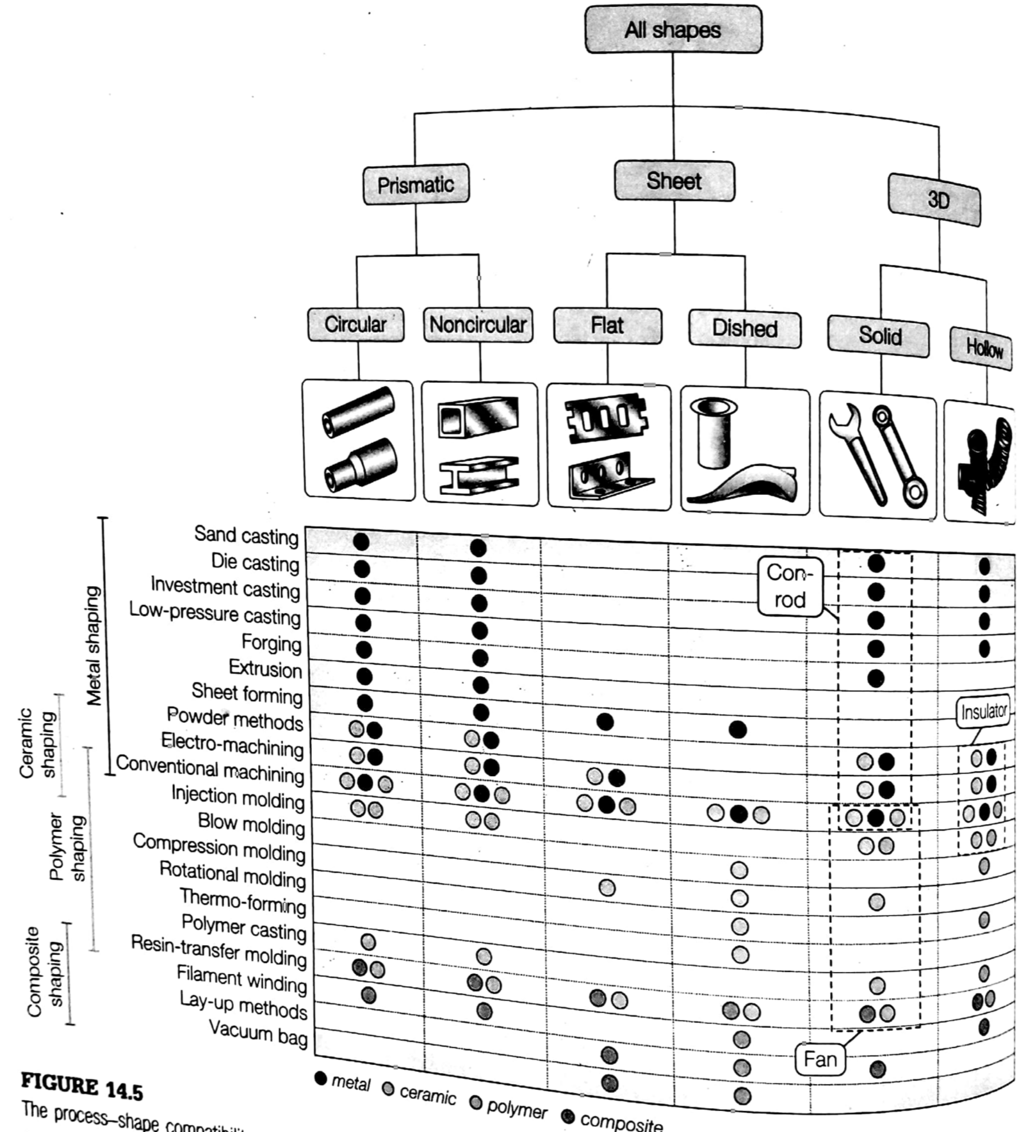


FIGURE 14.5

The process–shape compatibility matrix, showing the requirements of the case studies. A summary of the material compatibility appears at the left. The intersection of this selection stage and the last one narrows the choice.

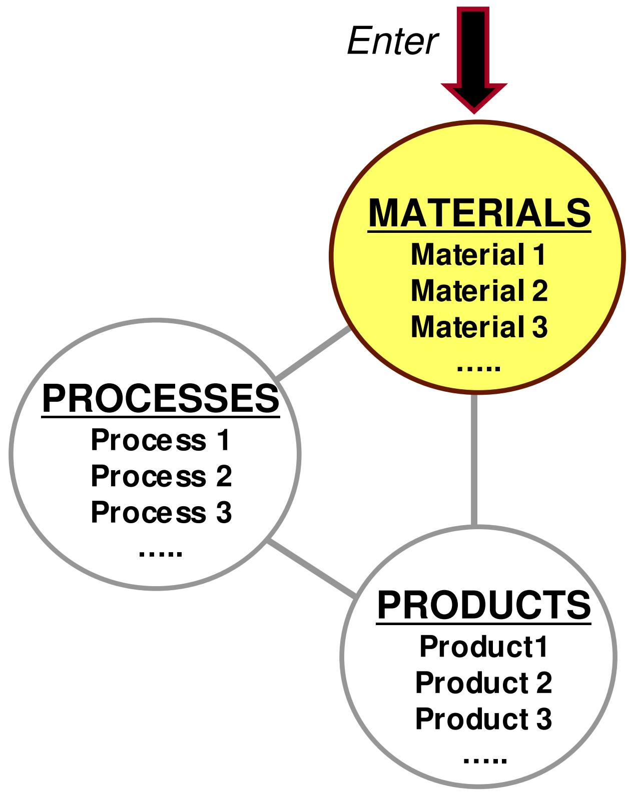
Selection by Technical Analysis

Select on material properties alone

Find material that has

- Attribute 1 < C_1 **(Density, ρ)**
- Attribute 2 > C_2 **(Modulus, E)**
- Attribute 3 > C_3 **(Strength, σ)**
- Attribute 4 = C_4 **(Poisson, ν)**

Multiple constraints



Process Material Relationship

Select on processability and material properties

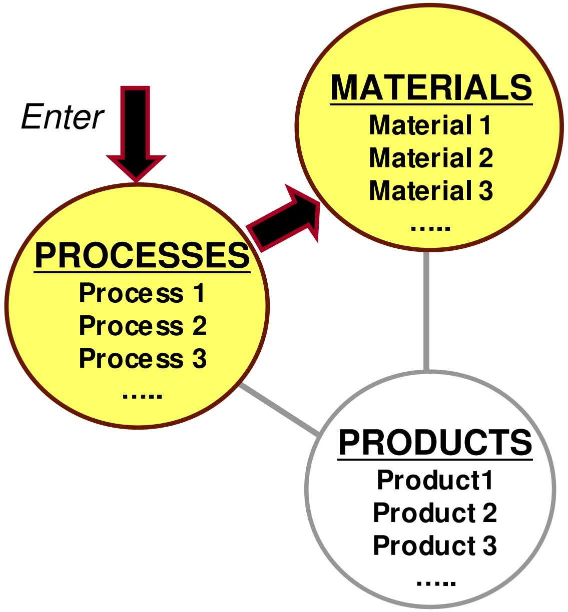
Find material that of type

"INJECTION MOULDABLE"

and has

- Attribute 1 > C_1
- Attribute 2 > C_2
- Attribute 3 < C_3
- Attribute 4 < C_4

Multiple constraints



Selection on Similarity

Select on similarity (and innovative substitution)

Find material that is like Material X, or like that of Product Z

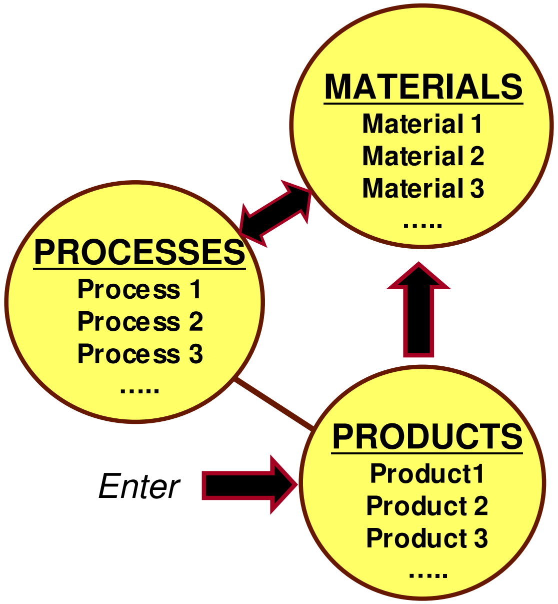
but has

- Attribute 1 > C_1
- Attribute 4 < C_4

Additional constraints

and is of type

"SAND-CASTABLE"



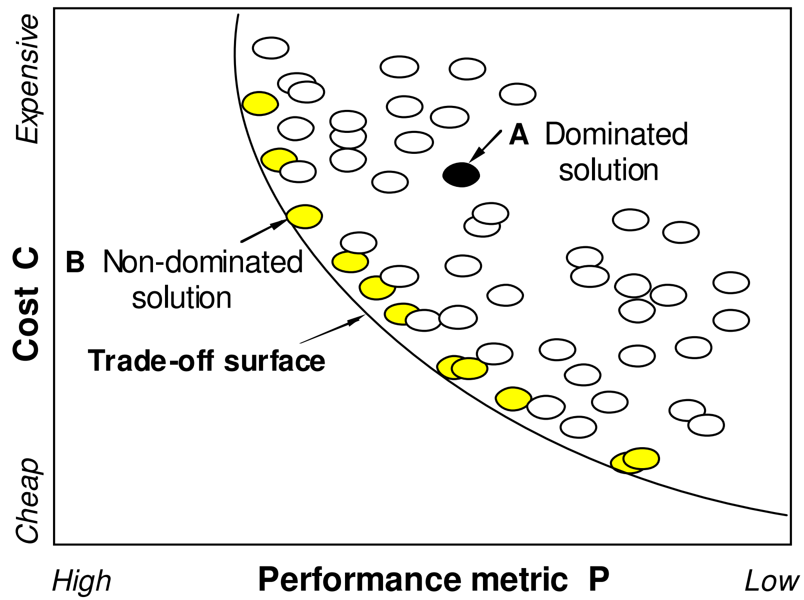
- **How balance objectives ? eg**

Performance, P } Conflicting objectives
Cost, C

- **Plot performance metric P against cost metric C**

- **A "solution",** is a material with a given combination of cost and performance

- **Dominated** and **non-dominated** solutions

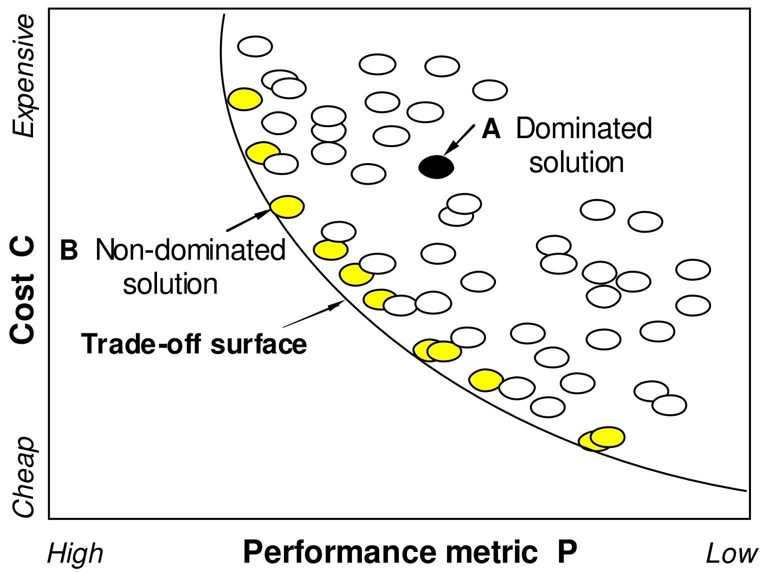


Multi-objective Optimization

- ***Solution:*** a viable choice, meeting constraints, but not necessarily optimum by either criterion.

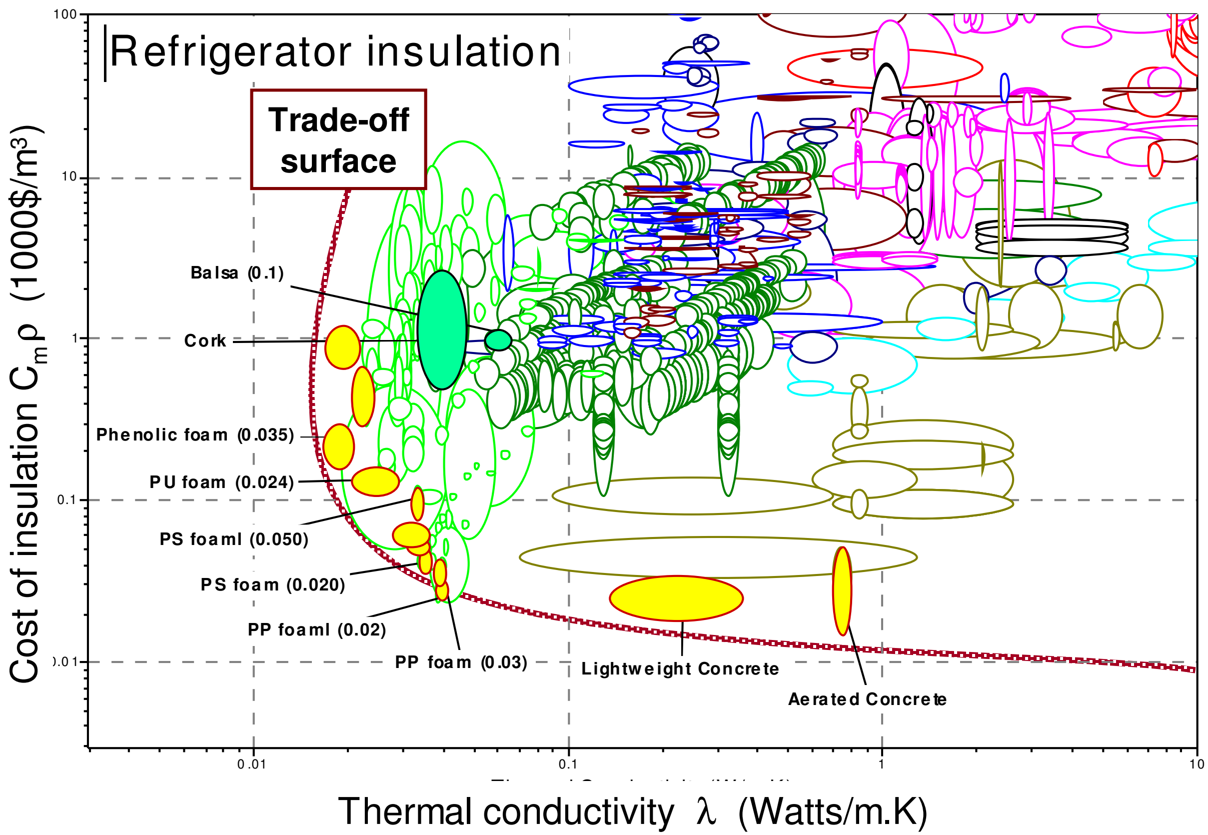
- ***Dominated solution (A):*** some other solution is better by both metrics

- ***Non-dominated solution (B):*** no one other solution is better by both metrics



- The **trade-off surface** (or Pareto front) is the surface on which the non-dominated solutions lie
- Use **intuition** to select
- Form a **value function**: a composite objective

Multi-objective Optimization



ME 423: Machine Design
Instructor: Ramesh Singh

Summary

- Engineering Materials
- Material Property Charts
- Material Indices
- Material Selection Methodology by Ashby
- Multi-objective Optimization