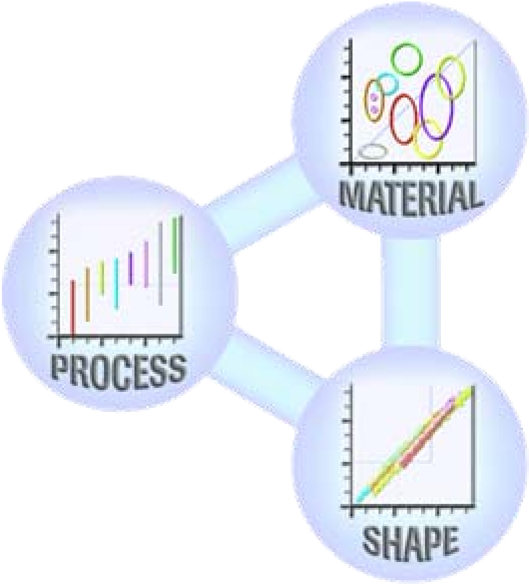
Unit 1. Mapping the World of Materials:
the first step in exploration and selection



New approaches to Materials Education
- a course authored by
Mike Ashby and Dave Cebon
Cambridge, UK

Difficulty level 1

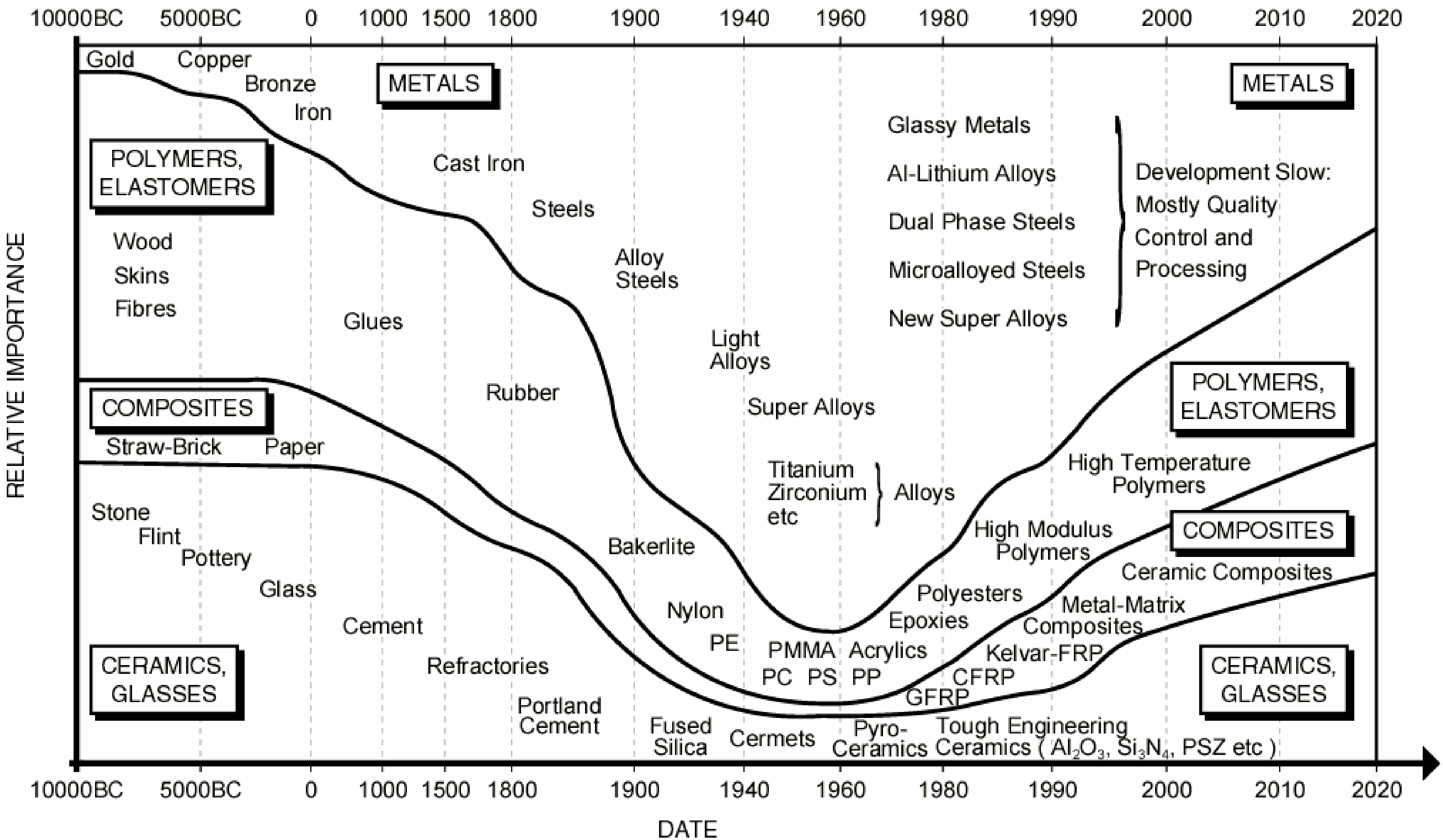
Outline

- **History -- the evolution of materials**
- **Materials and their attributes**
- **The nature of materials data**
- **Exploring relationships: Material Property Charts**
- **The design process**
- **Matching material to design: screening and ranking**

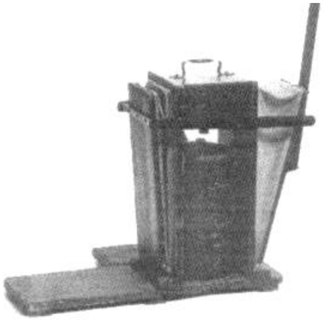
Resources:

- "Materials Selection in Mechanical Design", ("The Text") by M.F. Ashby, Butterworth Heinemann, Oxford, 1999, Chapters 1 - 4.
- The Cambridge Material Selector *(CES 4)* software -- Granta Design, Cambridge (www.grantadesign.com)

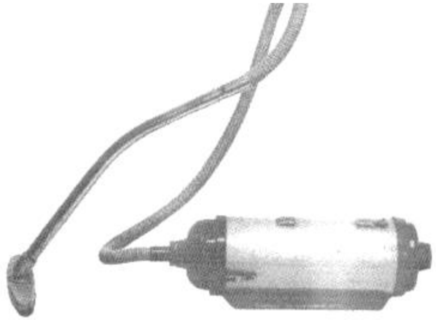
The evolution of materials



FUNCION: Limpieza



(a) 1905



(b) 1950

(c) 1985

(d) 1997

Modèle	Matériaux dominants	Puissance (W)	Poids (kg)
1900	Bois, toile, cuir	50	10
1950	Acier doux	300	6
1985	ABS et PP	800	4
1997	PP, PC, ABS	1 200	6,3

Sistema « manual »→Sistema mecanico

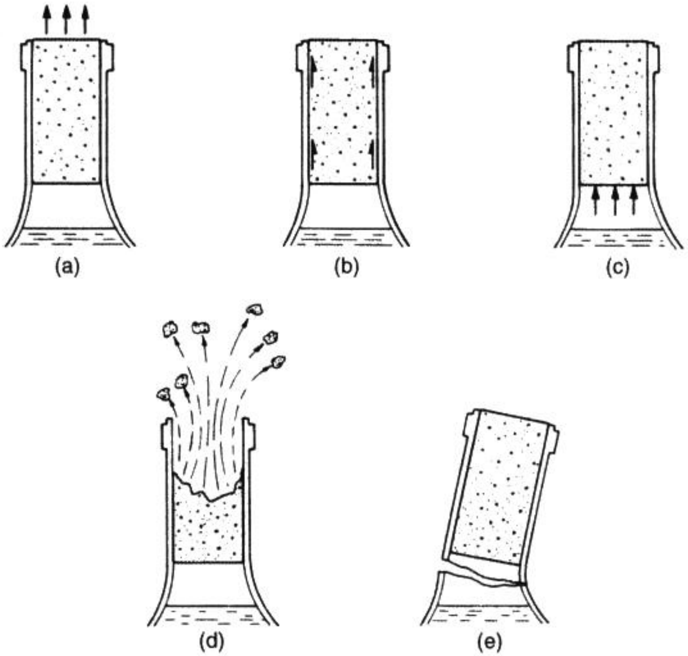
Recipiente y « trapitos » (1905)

↓

Tubo con ventilador (1950)

Necesidad subjetiva: beber el vino,

Necesidad objetiva: destapar la(s) botella(s)



Necesidad→Funcion: extraer el corcho

« bien »:rapidamente,sin daño ni « desgaste »

Soluciones conceptuales para la Funcion:

- **-la traccion axial (a),**
- **-el cisaille (b),**
- **-empuje: hacia afuera (…y hacia adentro!..) (c),**
- **-destrozarlo (d)!**
- **-cortar el cuello de la botella …(« sablazo!») (e).**

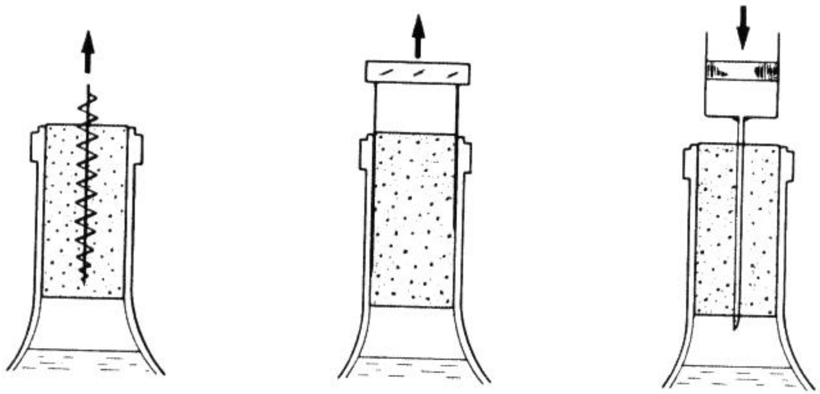
Applicacion de las soluciones conceptuales (funcionamiento)

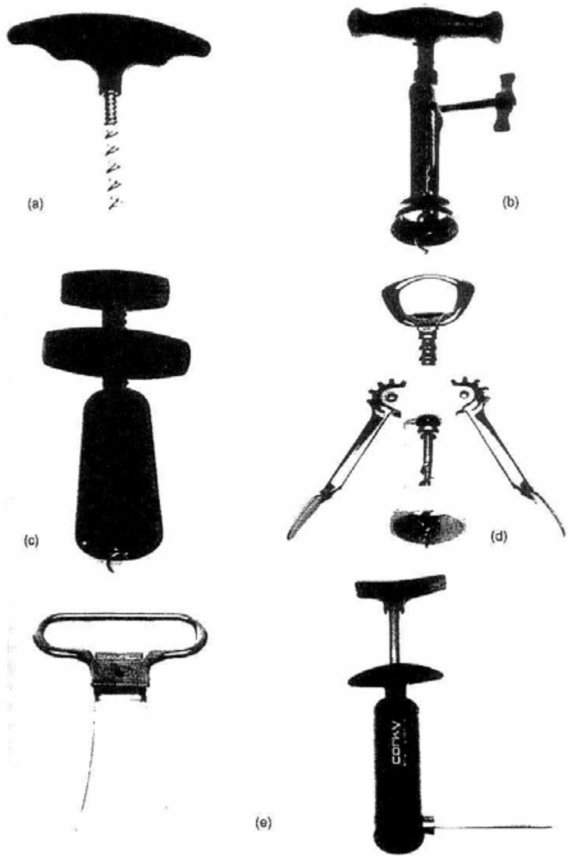
-Tornillo y tension (a,b,c,d),

-Laminas finas y elasticas

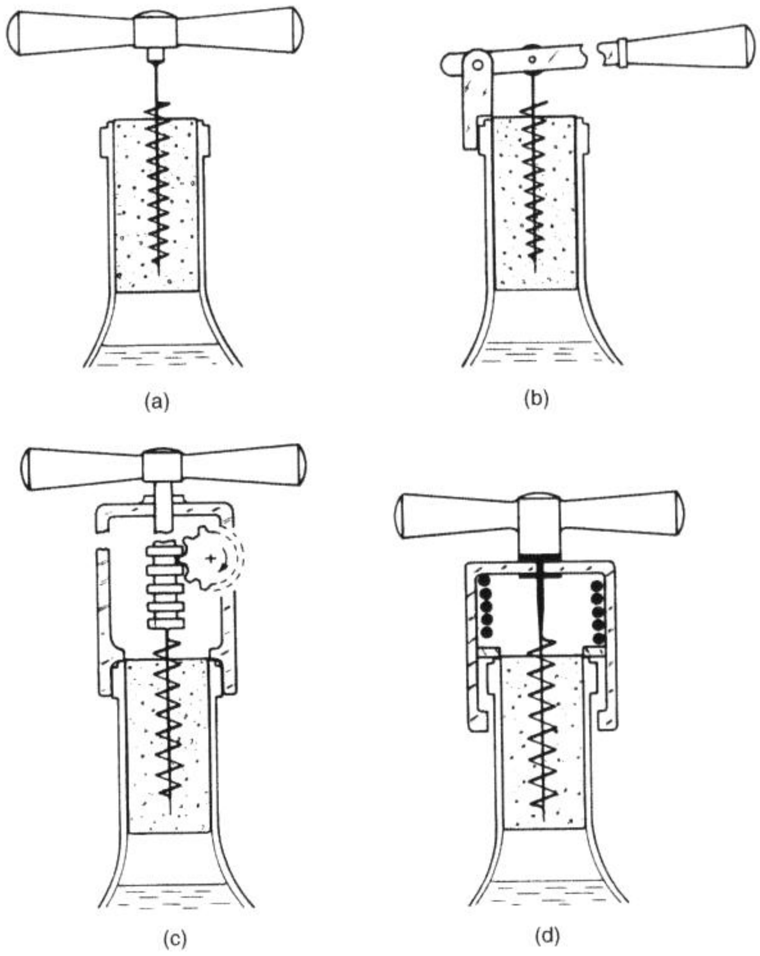
(apresar el corcho y cisaille, e),

-presion de aire interior (f).





Variaciones sobre el mismo tema: extraccion por traccion.



-Applicacion :

(a) solucion clasica « a pulso ».

-Applicaciones indirectas del esfuerzo:

(b) palanca,

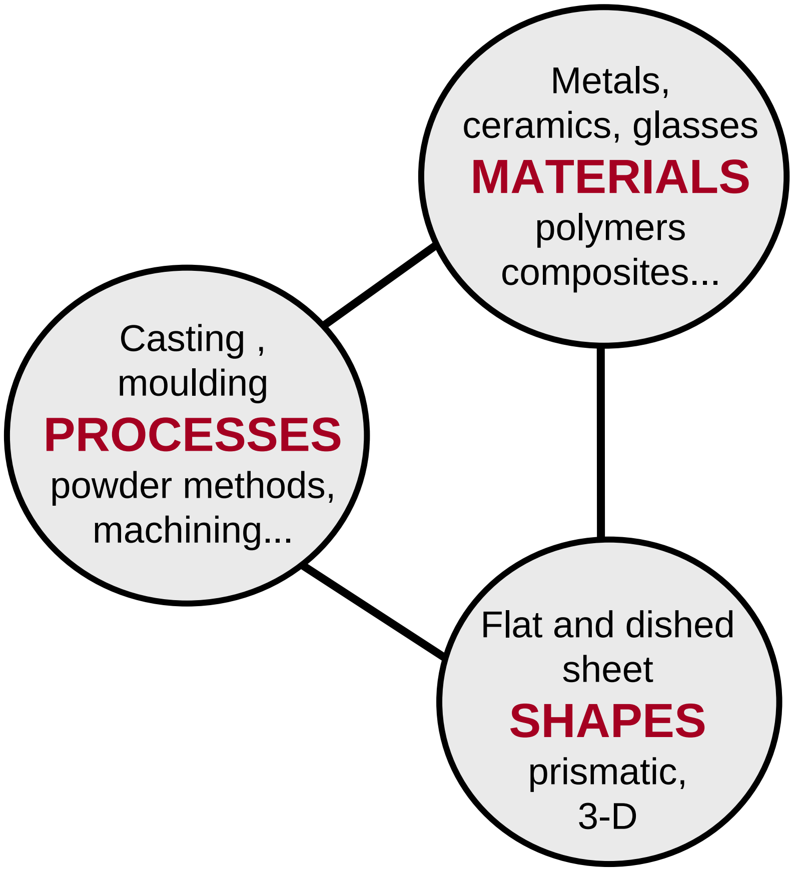
(c) cremallera,

(d) con ayuda de resorte precomprimido.

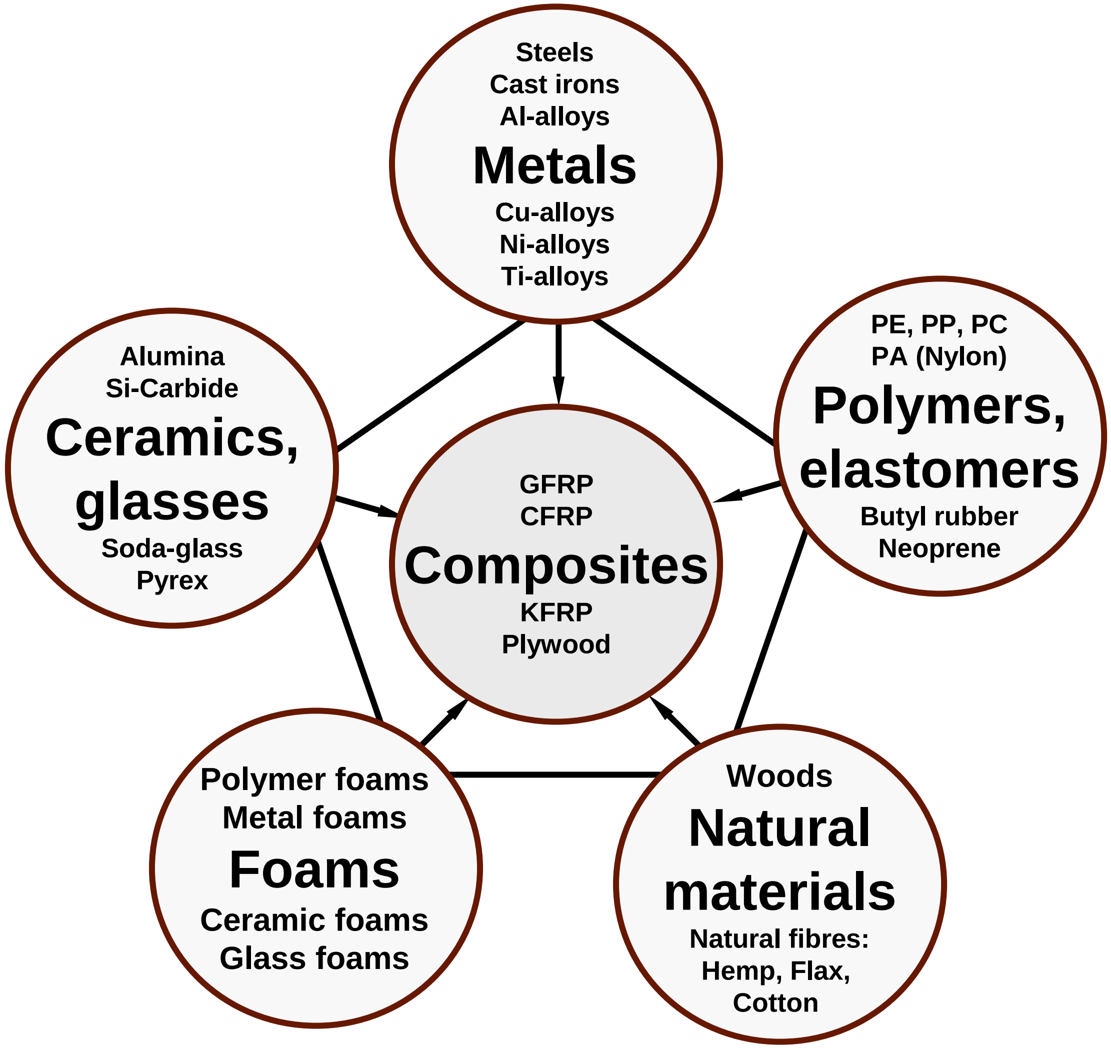
Propiedades de los materiales interviniendo en las fases De concepcion y realizacion.

Type	Propriété	Symbole	Unité
Général	Coût	C_m	$/kg
	Densité	ρ	$kg \cdot m^{-3}$
Mécanique	Modules d'élasticité (Young, cisaillement, compressibilité)	E, G, K	GPa
	Résistance mécanique	σ_f	MPa
	Énergie de rupture	G_c	$kJ \cdot m^{-2}$
	Ténacité	K_c	$MPa \cdot m^{1/2}$
	Capacité d'amortissement	η	–
	Limite d'endurance	σ_e	MPa
Thermique	Conductivité thermique	λ	$W \cdot K^{-1} \cdot m^{-1}$
	Diffusivité thermique	a	$m^2 \cdot s^{-1}$
	Chaleur spécifique	C_p	$J \cdot K^{-1} \cdot kg^{-1}$
	Température de fusion	T_f ou T_m	K
	Température de transition vitreuse	T_g	K
	Coefficient de dilatation thermique	α	K^{-1}
	Résistance au choc thermique	ΔT	K
	Résistance au fluage	–	–
Usure, corrosion	Coefficient d'usure d'Archard	k_A	MPa^{-1}
	Vitesse de corrosion	K	mm/an
	Constante de vitesse parabolique d'oxydation	k_p	$m^2 \cdot s^{-1}$

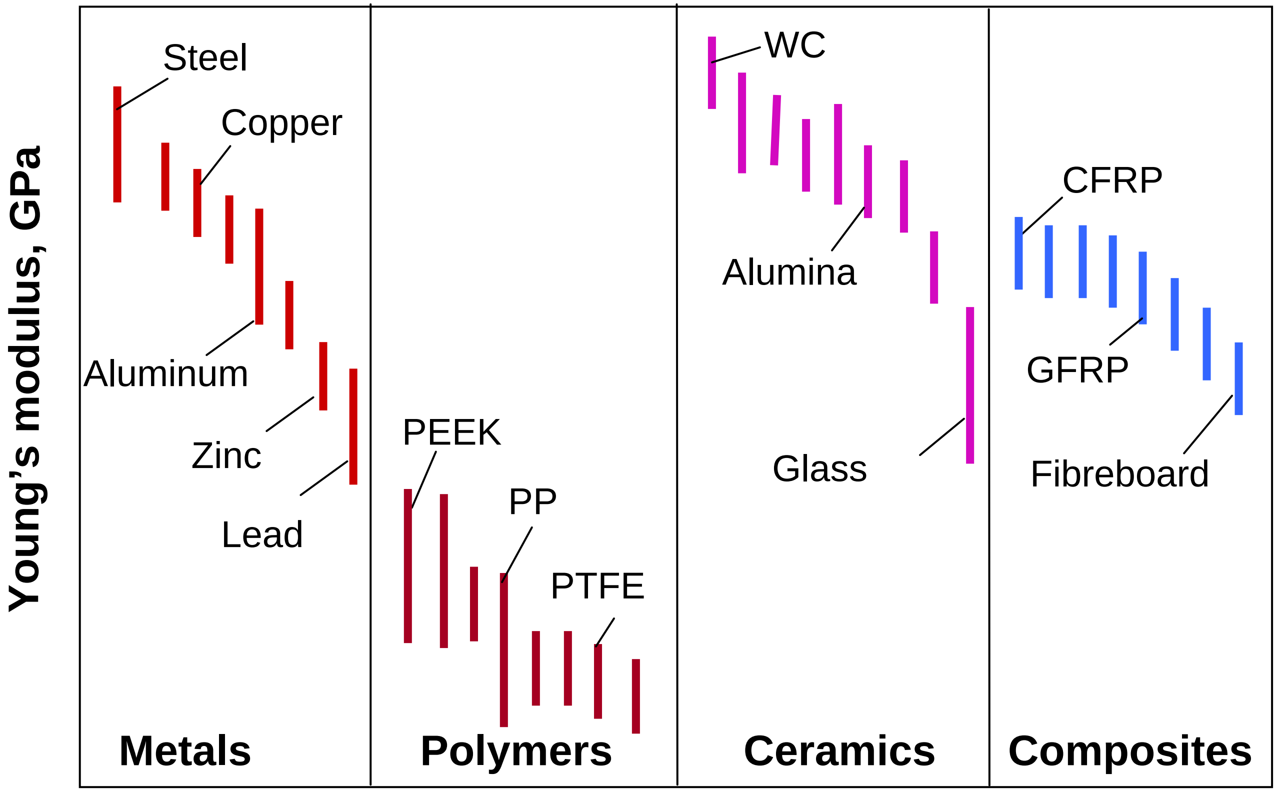
Materials, process and shape



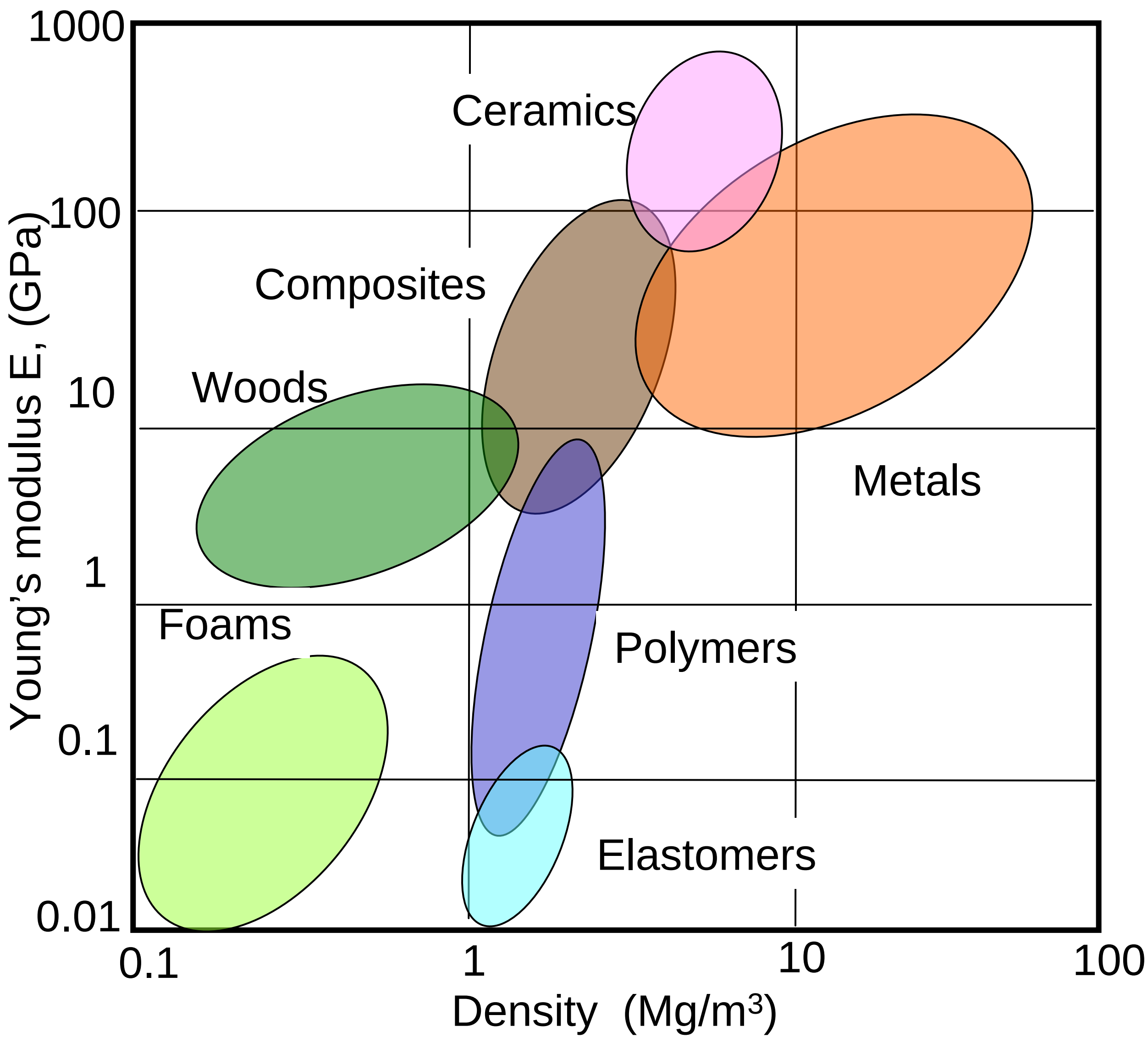
The world of materials



Clasificacion de una Propiedad (CES→1)

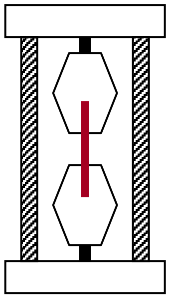


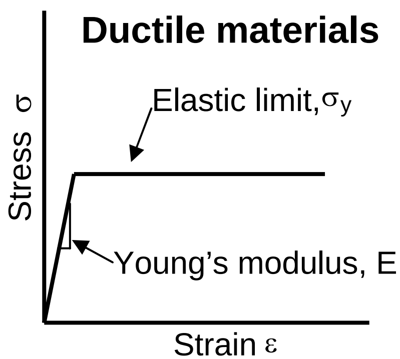
Clasificacion segun interaccion de Propiedades (CES→2)

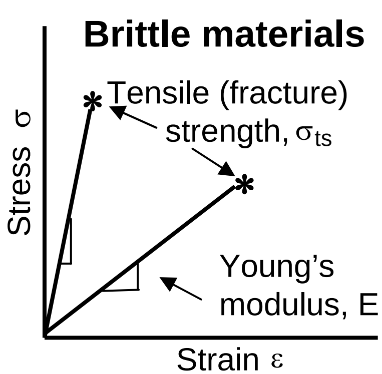


Basic material properties

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

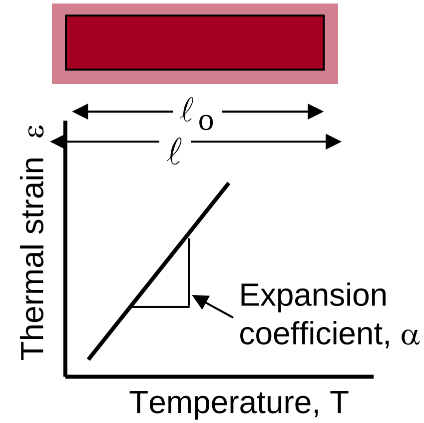
Expansion: Expansion coeff. α, 1/K

Conduction: Thermal conductivity λ, W/m.K

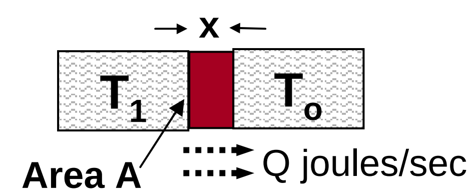
Electrical

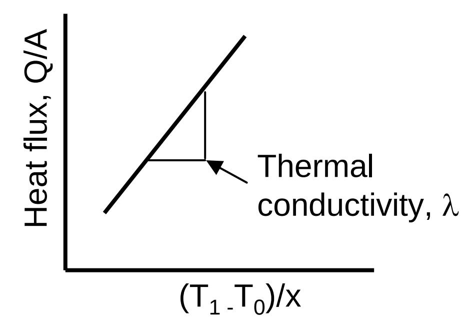
Conductor? Insulator?

Thermal expansion



Thermal conduction





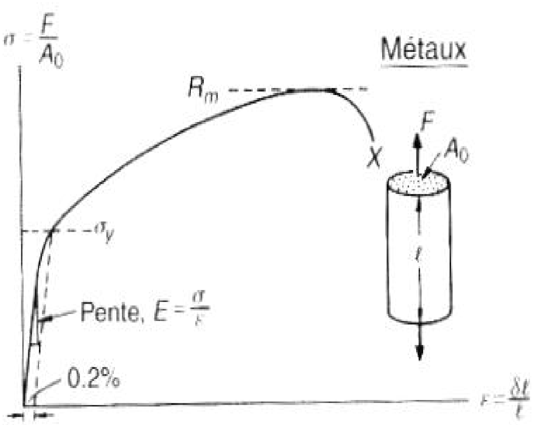
Mechanical

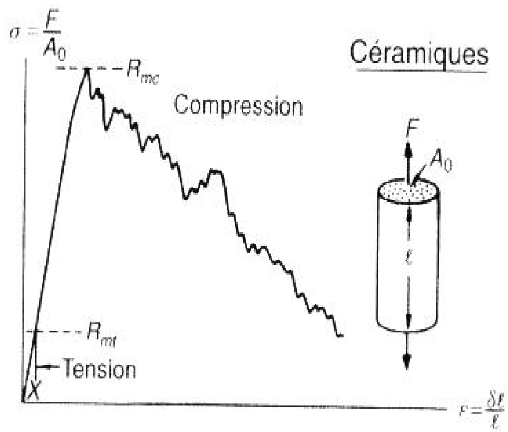
Stiffness: Young’s modulus E, GPa

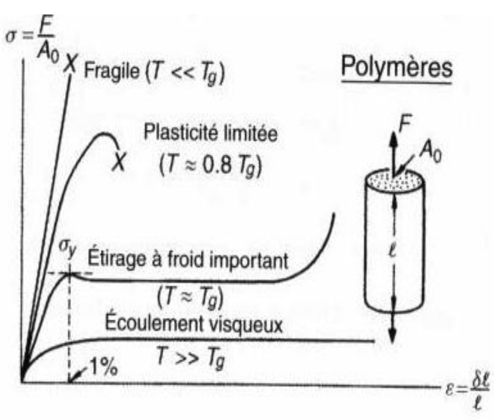
Strength: Elastic limit σ_y , MPa

Fracture strength: Tensile strength σ_{ts} , MPa

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







Elasticidad medio isotropo y homogeneo (CES→5).

1-3- Stresses $(\sigma_{ij} = C_{ijKl}\varepsilon_{ij})$

$$\sigma_{xx} = (\lambda+2G)\varepsilon_{xx} + \lambda\varepsilon_{yy} + \lambda\varepsilon_{zz}$$
$$\sigma_{yy} = (\lambda+2G)\varepsilon_{yy} + \lambda\varepsilon_{xx} + \lambda\varepsilon_{zz}$$
$$\sigma_{zz} = (\lambda+2G)\varepsilon_{zz} + \lambda\varepsilon_{xx} + \lambda\varepsilon_{yy}$$

$$\sigma_{xy} = 2G\gamma_{xy}$$
$$\sigma_{yz} = 2G\gamma_{yz} \qquad \left\{G = \frac{E}{2(1+\upsilon)}\right\}$$
$$\sigma_{zx} = 2G\gamma_{zx} \qquad \lambda = \frac{\upsilon E}{(1+\upsilon)(1-2\upsilon)}$$
$$\upsilon = \frac{E-2G}{2G}$$

$$\varepsilon_{xx} = \frac{1}{E}\left[\sigma_{xx} - \upsilon(\sigma_{yy} + \sigma_{zz})\right] \quad \varepsilon_{xy} = \frac{1}{2G}\sigma_{xy}$$
$$\varepsilon_{yy} = \frac{1}{E}\left[\sigma_{yy} - \upsilon(\sigma_{xx} + \sigma_{zz})\right] \quad \varepsilon_{yz} = \frac{1}{2G}\sigma_{yz}$$
$$\varepsilon_{zz} = \frac{1}{E}\left[\sigma_{zz} - \upsilon(\sigma_{xx} + \sigma_{yy})\right] \quad \varepsilon_{zx} = \frac{1}{2G}\sigma_{zx}$$

Plane stress

$\sigma_{xx} = \sigma_{yy} \quad \sigma_{zz} = 0$

Plane strain

$\varepsilon_{yy} = 0$

Modulos Elasticos (material isotropo)

E: modulo de Young

ν: coeficiente de Poisson

G: modulo de cizaille

K: modulo de compresibilidad

$$E = \frac{3G}{1 + G/3K} \qquad G = \frac{E}{2(1+\nu)}$$

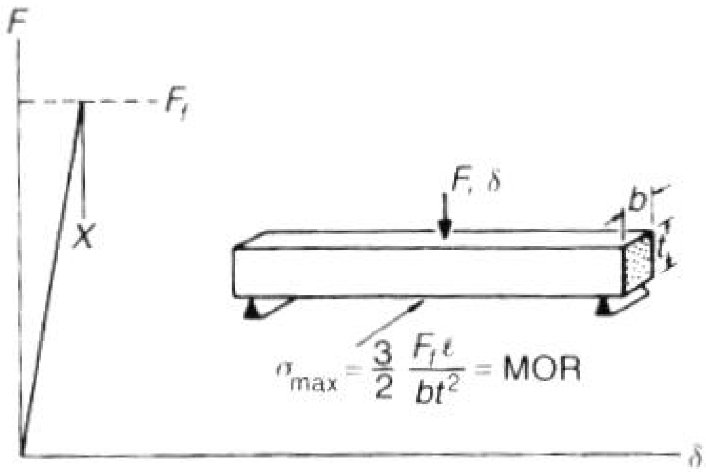
$$K = \frac{E}{3(1-2\nu)}$$

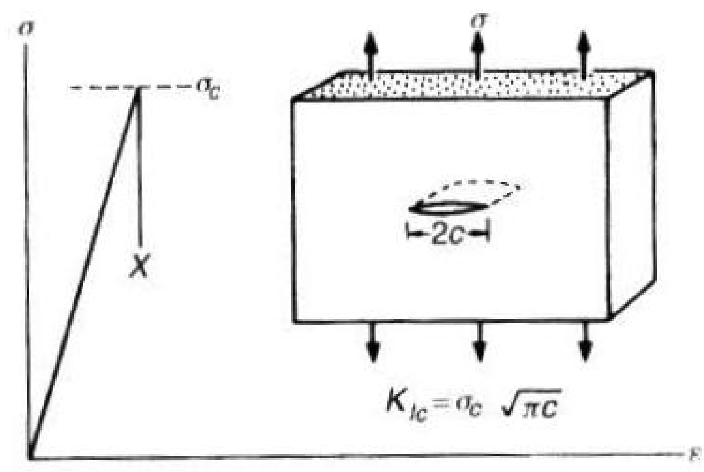
metales → $\nu \simeq 1/3$, $G \simeq \frac{E}{8}$, $K \simeq E$

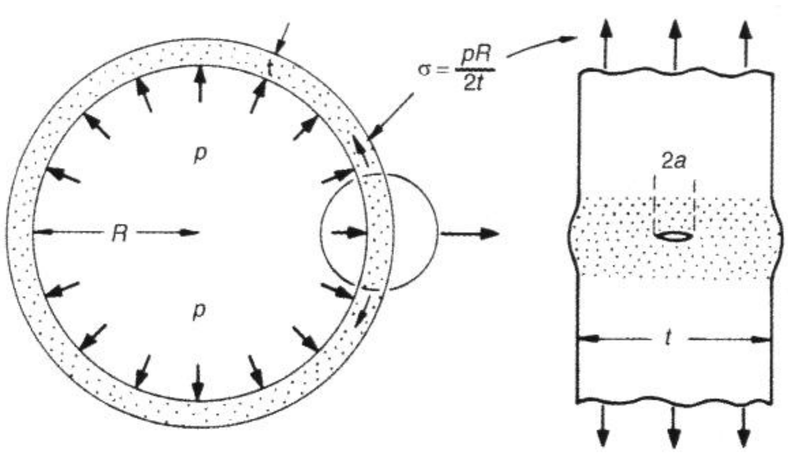
elastómeros → $\nu \simeq 1/2$, $G \simeq \frac{E}{3}$, $K \gg E$

Ensayos y Propiedades Mecanicas (CES→5)

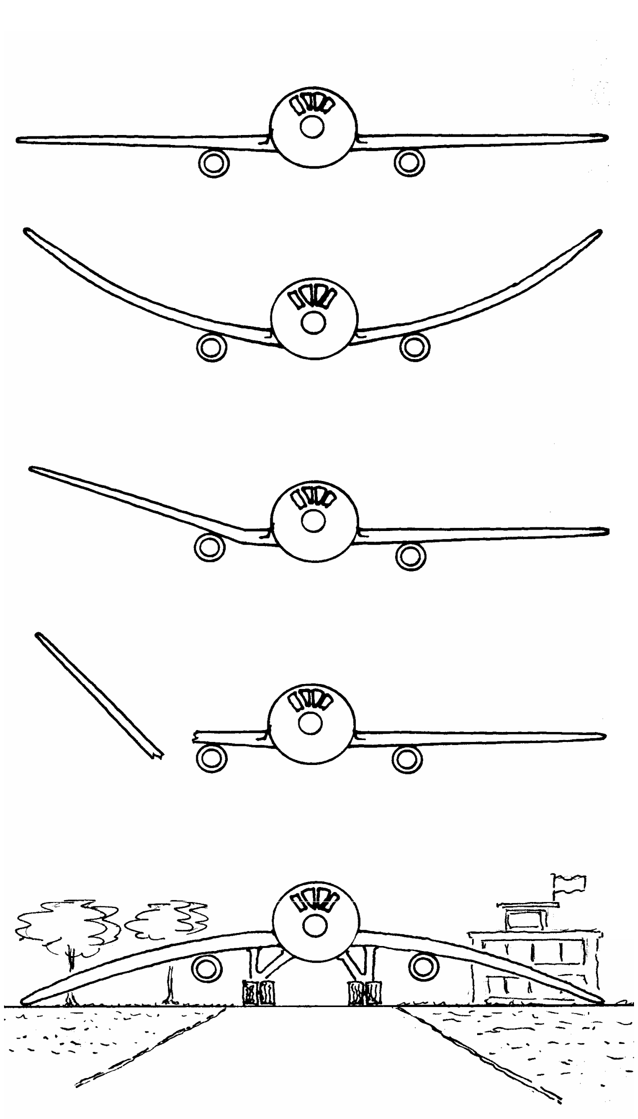
Fragilidad, Ruptura, defectos Criticos.







Mechanical properties illustrated



- ← **Stiff, Strong, Tough, Light** — **All OK !**
- ← **Not stiff enough (need bigger E)**
- ← **Not strong enough (need bigger σ_y)**
- ← **Not tough enough (need bigger K_{ic})**
- ← **Too heavy (need lower ρ)**

Materials para estructuras de aviones

Función

- transporte .. a menor costo!

  y con "seguridad" ! (civil)

- ir rápido … maniable (militar)

Solicitaciones distintas ↔ Requisitos distintos

***Alas: solicitaciones importantes**

⇒ la estructura no debe plastificarse

* **Fuselaje: solicitaciones menos importantes, sin embargo,**

⇒ la estructura debe ser rígida

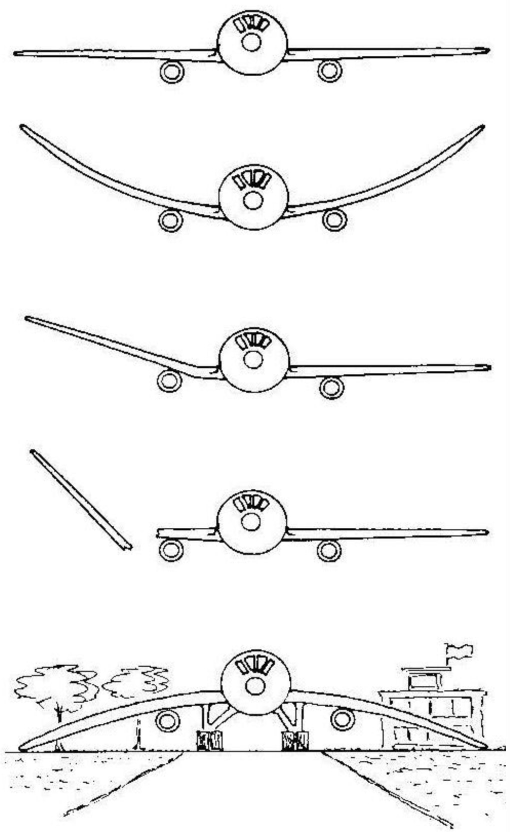
* **otros componentes; menos solicitados**

⇒ limitar la corrosión

Seguridad:

⇒ resistencia a la fatiga!

Mechanical properties illustrated



Problema 1

Optimización de la resistencia de placas en flexión (las alas), minimizando el peso. Que combinación de propiedades del material deben optimizarse?

⇒ Concepto noción de indice de rendimiento (performance).

Problema 2

Una parte de la estructura de un ala esta en tracción: asegurar una buena tenacidad. La parte alta está en compresión… y hay que evitar que se produzca un pandeamiento (inestabilidad).

⇒ Modos de solicitación diferentes … criterios distintos.

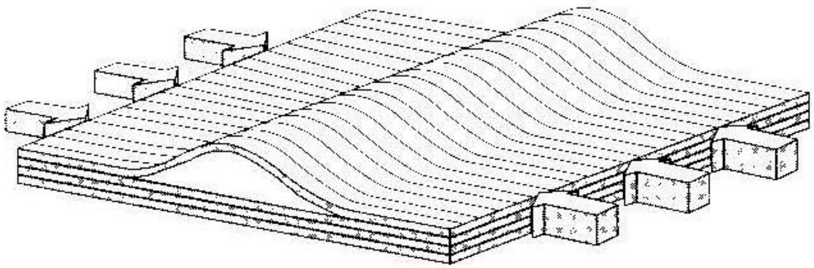
Inestabilidad de una placa en compresión

$$\sigma_c = K\frac{E}{1-\nu^2}\left(\frac{t}{b}\right)^2$$

$$K = f\left(\frac{a}{b}\right) \rightarrow \frac{a}{b} > 3$$

K = 3.29

$$\sigma = \frac{F}{b.t} < \sigma_c < K\frac{E}{1-\nu^2}\left(\frac{t}{b}\right)^2$$



…plt el espesor ⇒

$$t > \left(\frac{Fb(1-\nu^2)}{KE}\right)^{1/3}$$

y como el peso:

$$M = \zeta \cdot \underbrace{b \cdot t \cdot a}_{vol} \rightarrow \zeta \cdot b\left(\frac{F_b(1-\nu^2)}{KE}\right)^{1/3} \cdot a$$

$$Mliviana \equiv \frac{\zeta}{E^{1/3}} \rightarrow \frac{E^{1/3}}{\zeta}_{\max!}$$

Mechanical properties illustrated

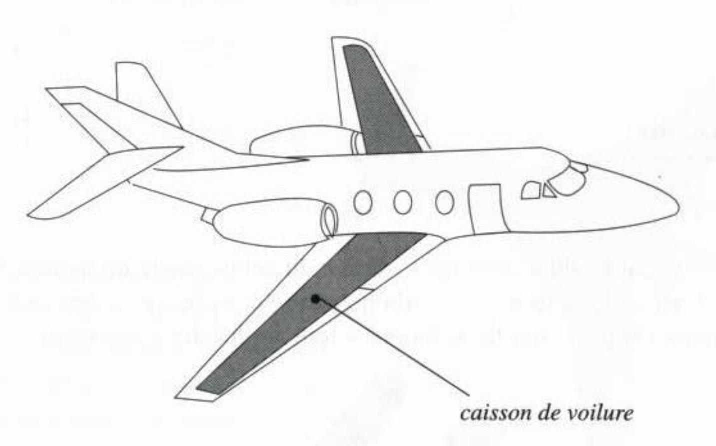
y el otro criterio es que σ_c debe quedar < a σ_y(yield)*

$$\sigma = \frac{F}{t.b} \Rightarrow \sigma_y \cdot t = \frac{F}{b}$$

$\Rightarrow$ como $M = \zeta \cdot b \cdot t \cdot a$

$$Mliviana \equiv \left(\frac{\zeta}{\sigma_y} \rightarrow \frac{\sigma_y}{\zeta} \right)_{max}$$

	E(Gpa)	σ_y(Mpa)	ζ(t/m^3)	$E^{1/3}/\zeta$	σ_y/ζ
Acero	215	1081	7.83	0.865	138
Aleación Ti6Al4V	110	830	4.43	1.08	187
Aluminio T-76	71.6	500	2.8	1.48	178
Aluminio T-3	73	345	2.77	1.5	124
Epoxy-C	129	1600	1.5	3.4	1070
Balsa	9.4	39	0.42	5.0	93



Mechanical properties illustrated

Balance

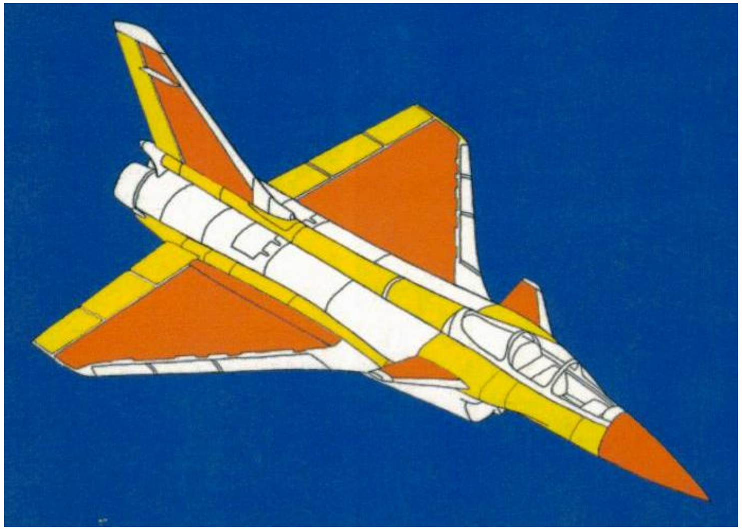
- Aleaciones de <u>Al</u>

  T_3 → parte en compresión

  T_{76} → parte en tracción

- acero no conviene
- titanio … caro! (en caso de crisis $!)
- Balsa!? (Ader, … 1900 ± 20)
- epoxy + C } excelente solución

pero carísima! (los militares sí!)



Mechanical properties illustrated

Criterios de selección:

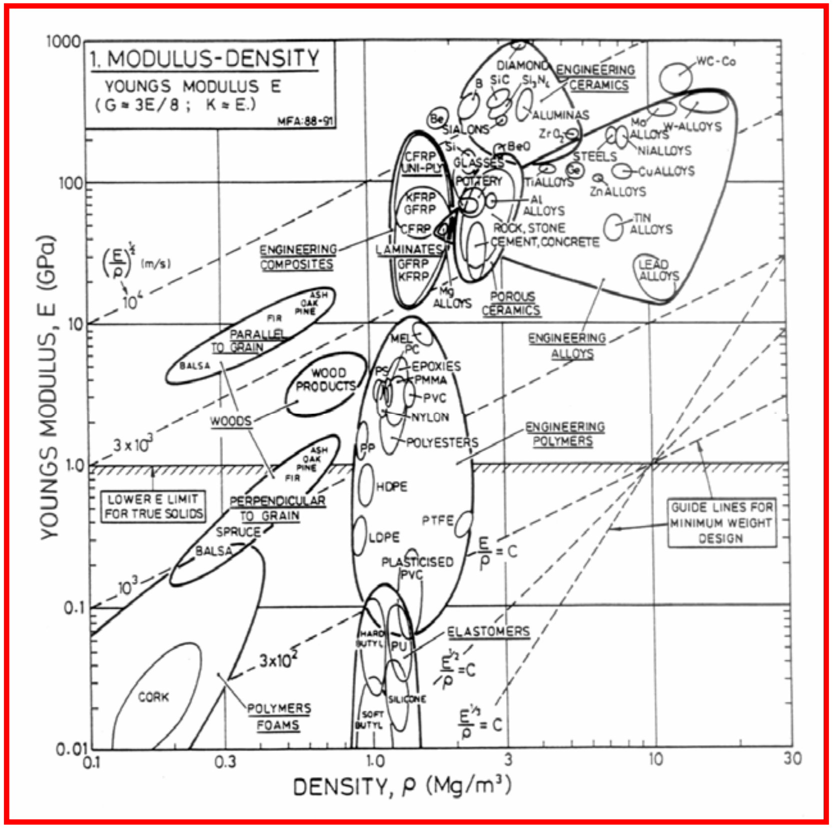
Optimizar combinaciones de propiedades

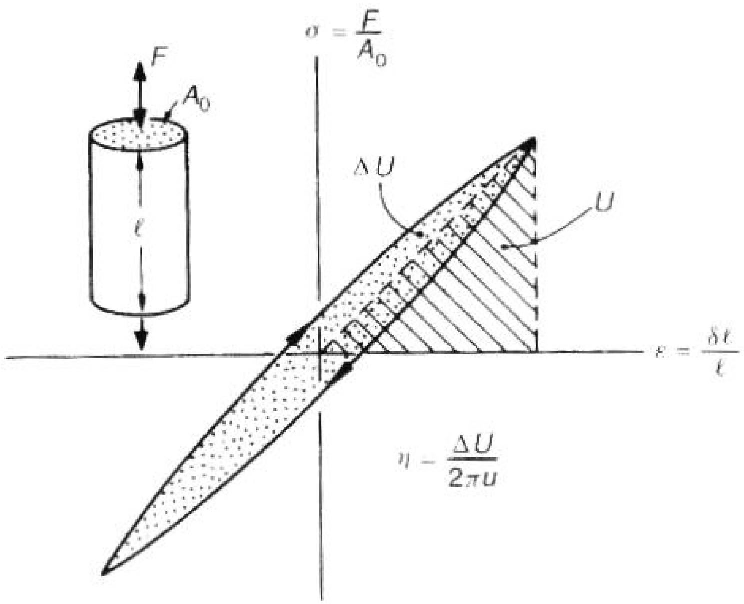
$$E^{1/3}/\zeta\ ;\ \sigma_y/\zeta$$

→ Mapas con una propiedad en cada eje

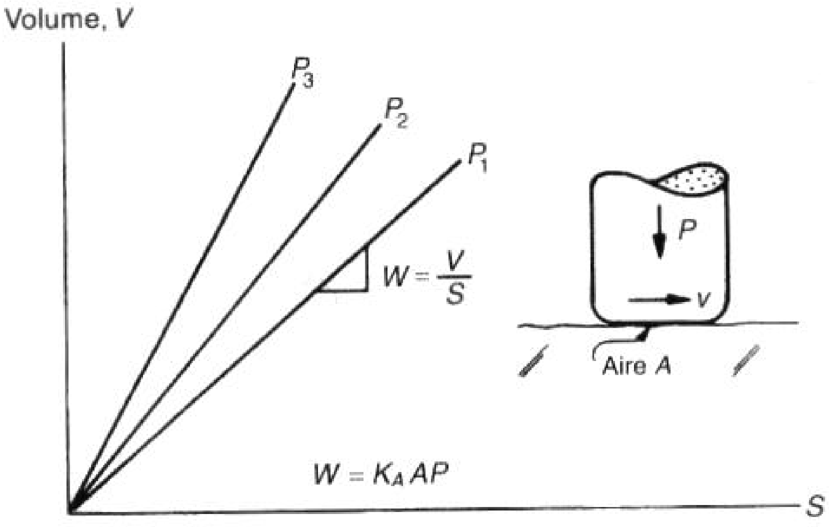
→ ..indices ⇒ potencias p.l.t escalas log/log

→ …lineas equi-"performacia" derechas





σ = F / A0
F
A0
ℓ
ΔU
U
ε = δℓ / ℓ
η = ΔU / 2πu



Volume, V
P3
P2
P1
W = V / S
P
v
Aire A
W = KA AP
S

Ensayos y Propiedades Mecanicas (Activacion Termica).

Creep Max/Min Serv. Temps. (CES→ 8,9,10).

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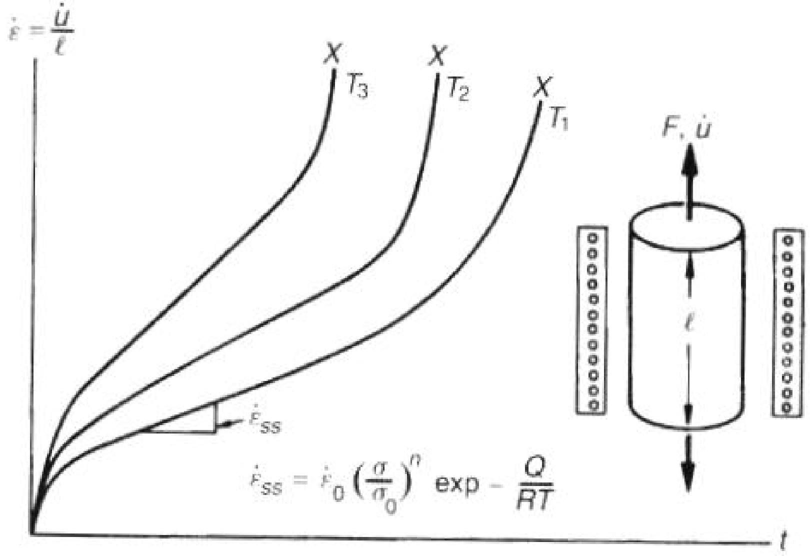

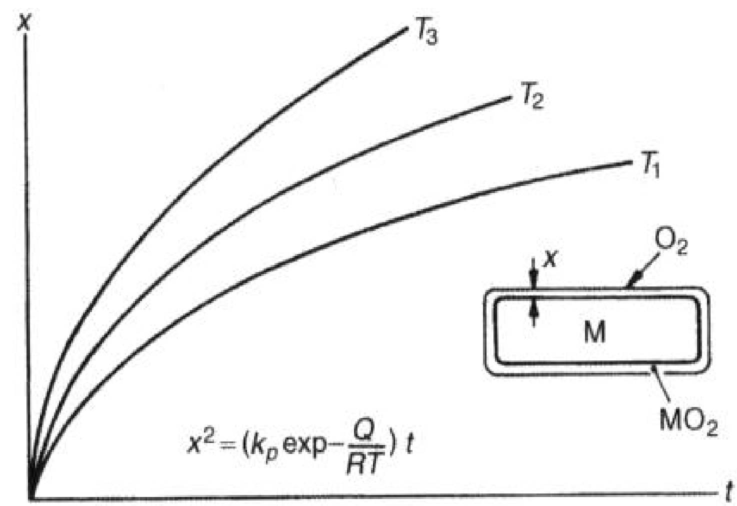

Propiedades Termicas (CES→ 11,12).

Coeficientes de Dilatacion y Conductividad Termica.

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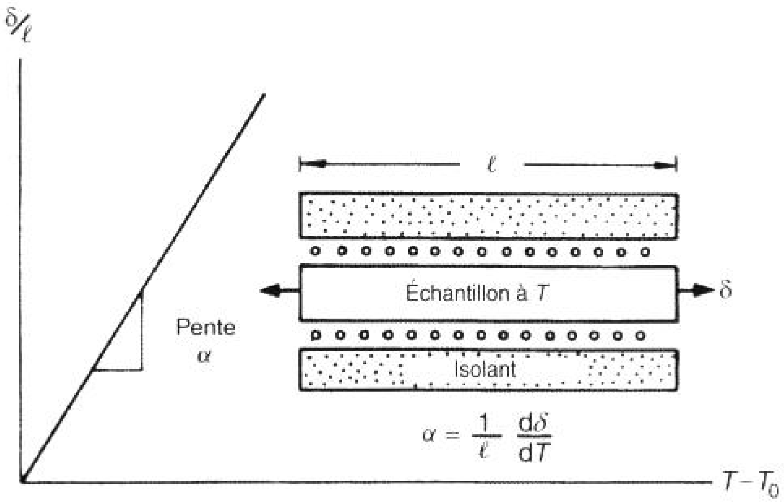
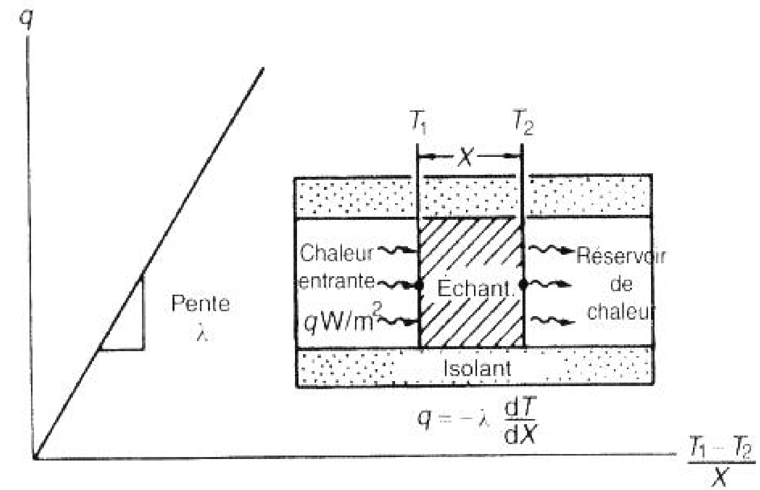




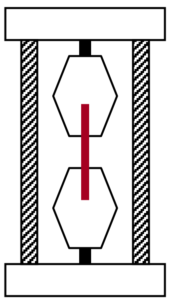
Materials information for design

The goal of design:

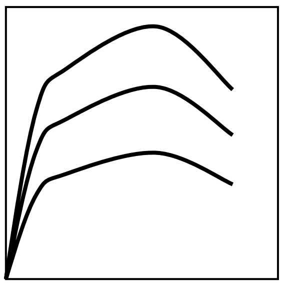
"To create products that perform their function effectively, safely, at acceptable cost"

What do we need to know about materials to do this? *More than just test data*.

Data capture → *Statistical analysis* → *Selection of material and process* → *Economic analysis and business case*



Test

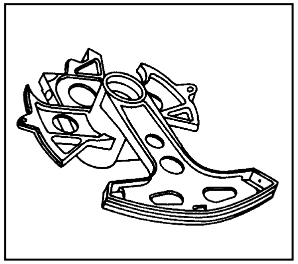


Test data

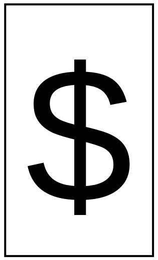
Mechanical Properties

Bulk Modulus	4.1 -	4.6 GPa
Compressive Strength	55 -	60 MPa
Ductility	0.06 -	0.07
Elastic Limit	40 -	45 MPa
Endurance Limit	24 -	27 MPa
Fracture Toughness	2.3 -	2.6 $MPa.m^{1/2}$
Hardness	100 -	140 MPa
Loss Coefficient	0.009-	0.026
Modulus of Rupture	50 -	55 MPa
Poisson's Ratio	0.38 -	0.42
Shear Modulus	0.85 -	0.95 GPa
Tensile Strength	45 -	48 MPa
Young's Modulus	2.5 -	2.8 GPa

Design data



Potential applications



Successful applications

Test, Test data, Design data: **Characterisation**

Potential applications, Successful applications: **Selection and implementation**

The nature of material data

- **Numeric:** properties measured by numbers: density, modulus, cost …other properties

Can extrude?

Good or bad in sea water?

- **Non-numeric:** properties measured by yes - no (Boolean) or poor-average-good type (Rankings)

Design guide lines

Case studies

Failure analyses

Established applications

- **Supporting information, specific:** what is the experience with the material?

Supplier information

FE modules

Standards and codes (ISO 14000)

Sector-specific approval (FDA, MilSpec)

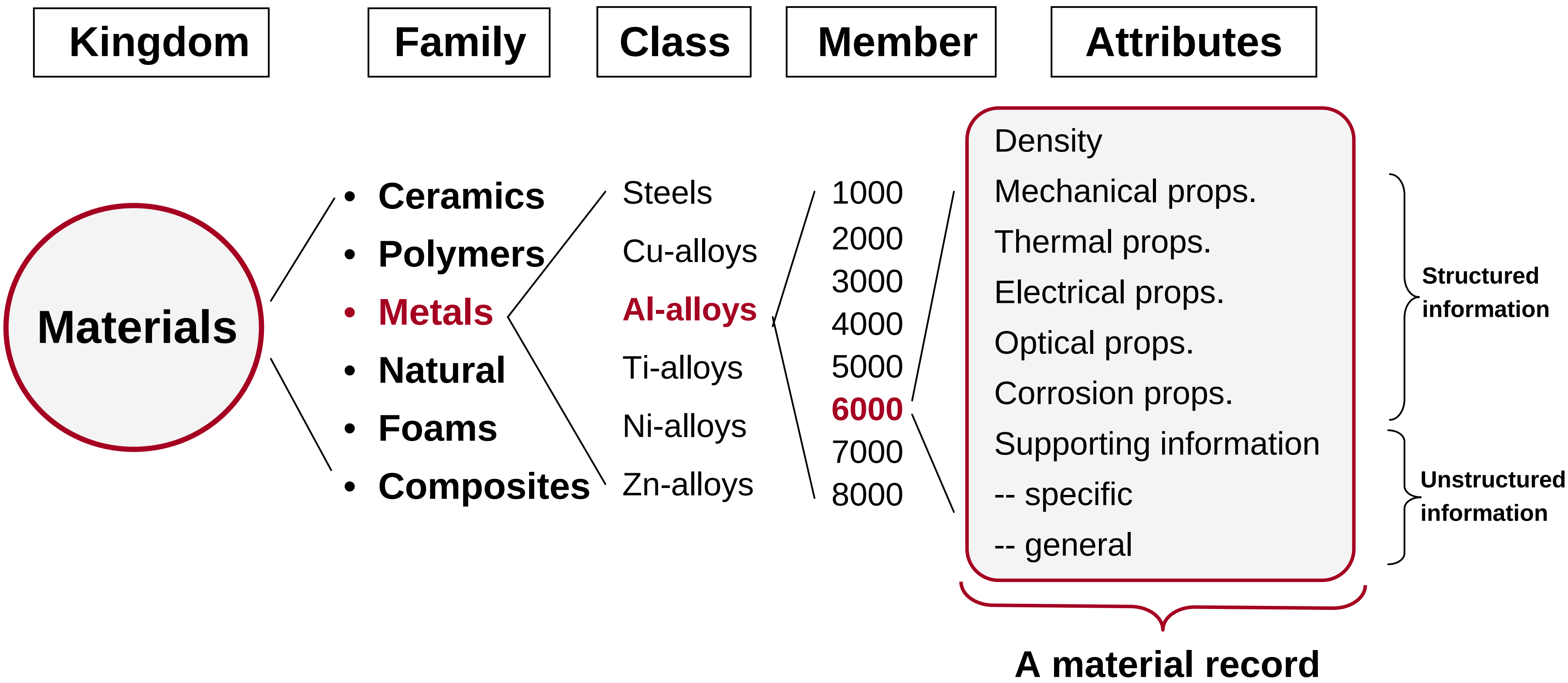
- **Supporting information, general:** what else do you need to know?

"Structured" and "Unstructured" data

Handbooks, data sheets

Reports, papers, the Web

Data organisation: materials



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

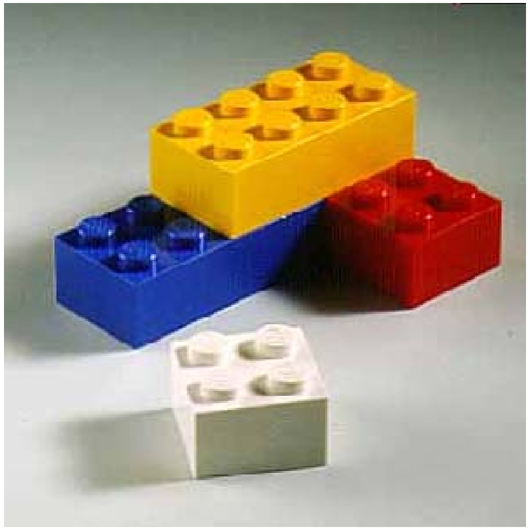
Transparent or opaque?	Opaque

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

*Using the *CES 4* Level 2 DB

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 syrene. 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.

*Using the *CES 4* Level 2 DB

Data, perspective and comparisons

- Handbooks, compilations (see Chapter 13 of The Text)
- Suppliers' data sheets
- The Worldwide Web (e.g. www.matweb.com)

BUT: no perspective, or comparison between material classes

Example: Typical properties of wrought Al-alloys (extract)

Alloy and temper	Tension: Strength, ksi: Ultimate	Tension: Strength, ksi: Yield	Tension: Elongation, % in 2 in.: 1/16 in. thick specimen	Tension: Elongation, % in 2 in.: 1/2 in. dia. specimen	Hardness: Brinnell number 500 kg load 10 mm ball	Shear: Ultimate shearing strength, ksi	Fatigue: Endurance[3] limit, ksi	Modulus: Modulus[4] of elasticity, ksi × 10^3
5652-HO	28	13	25	30	47	18	16	10.2
5652-H32	33	28	12	18	60	20	17	10.2
5652-H34	38	31	10	14	68	21	18	10.2
5652-H36	40	35	8	10	73	23	19	10.2
5652-H38	42	37	7	8	77	24	20	10.2
5657-H25	23	20	12	. .	40	12	. .	10.0
5657-H38, H28	28	24	7	. .	50	15	. .	10.0
6061-O	18	8	25	30	30	12	9	10.0
6061-T4, T451	35	21	22	25	65	24	14	10.0
6061-T6, T651	45	40	12	17	95	30	14	10.0
Alclad 6061-O	17	7	25	. .	. .	11	. .	10.0
Alclad 6061-T4, T451	33	19	22	. .	. .	22	. .	10.0
Alclad 6061-T6. T651	42	37	12	. .	. .	27	. .	10.0

Using CES 4 to find data

• Three levels of database (levels 1,2 and 3)

Finding data ("browsing"):

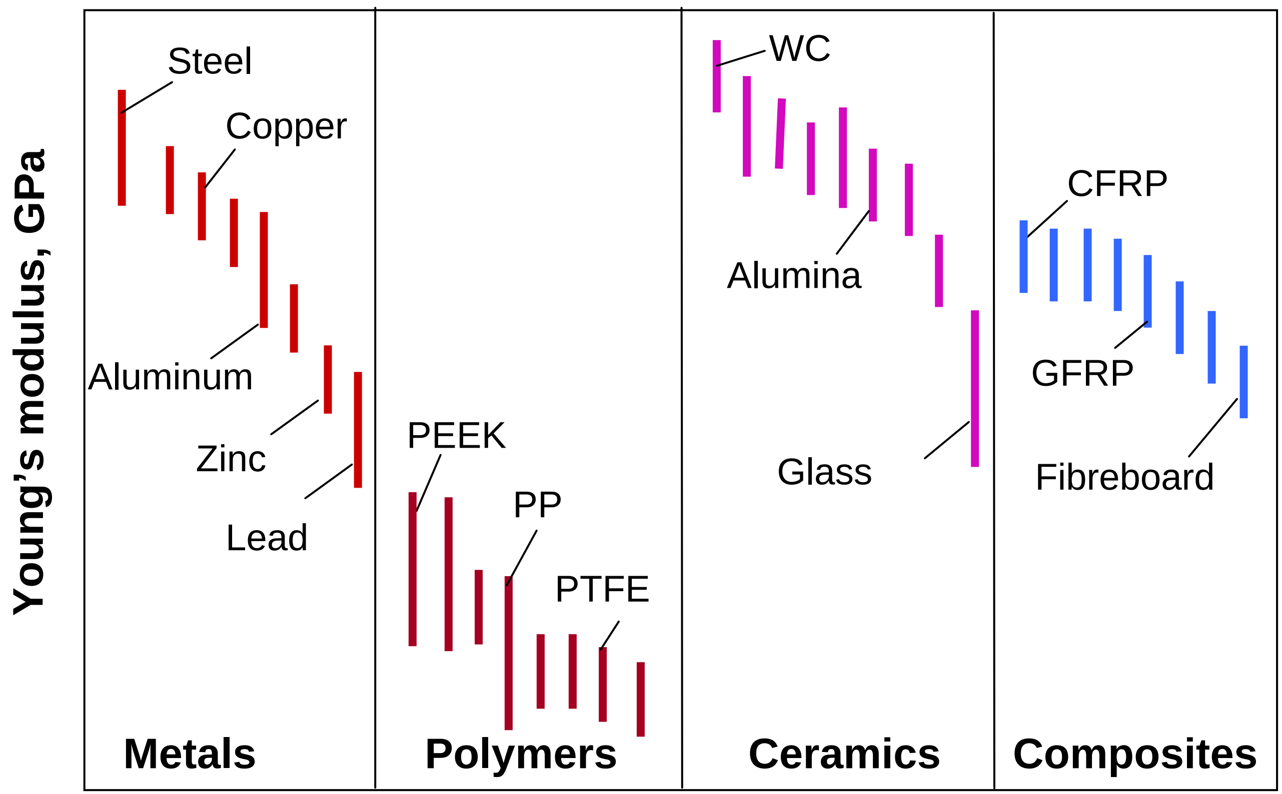
- Locate candidate on MATERIALS tree and double click, or
- Use the SEARCH facility to find all records contain candidate name, or trade-name, or application

Demo: finding data for materials

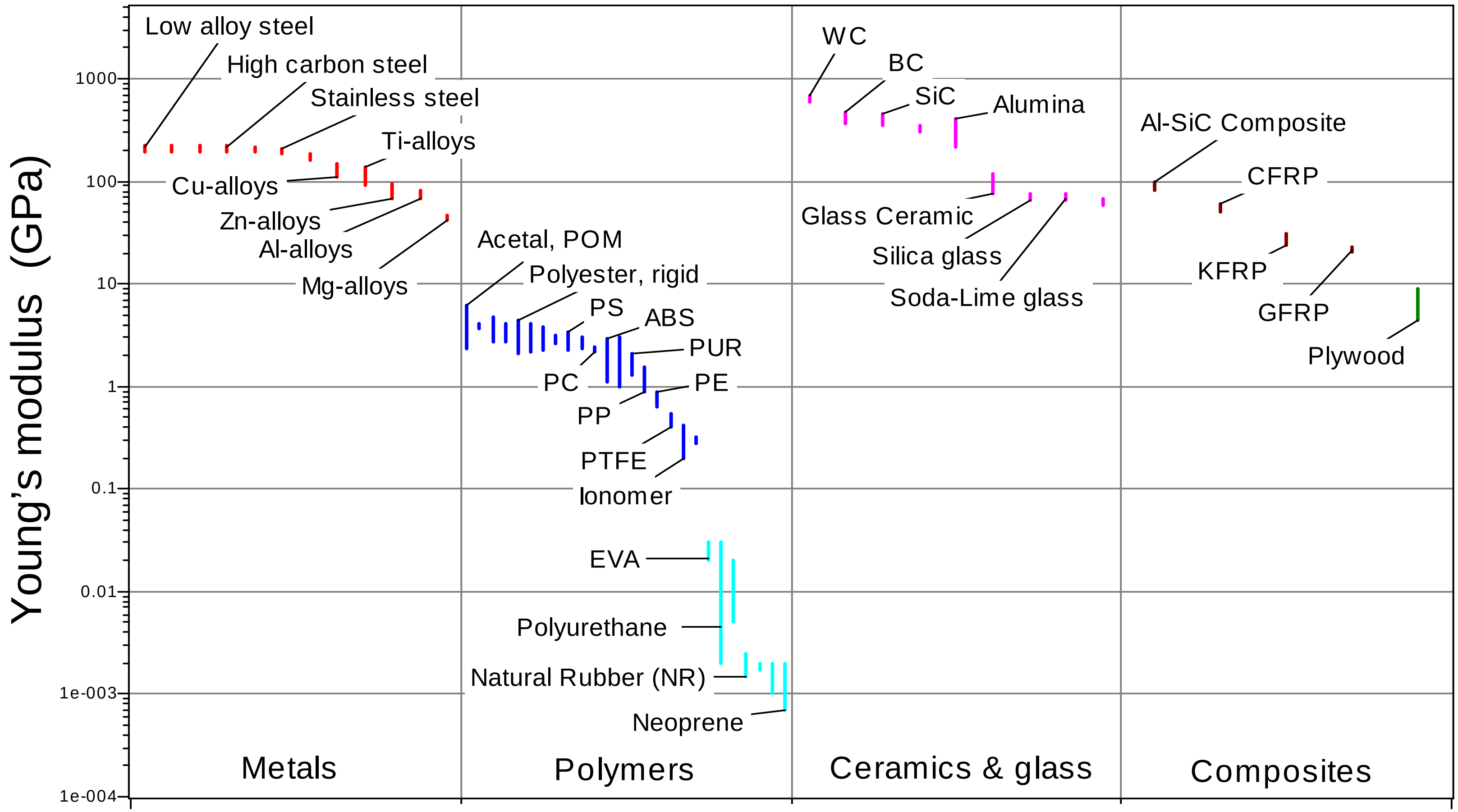
Relationships and comparisons

- Material bar-charts
- Material property charts

Relationships: property bar-charts

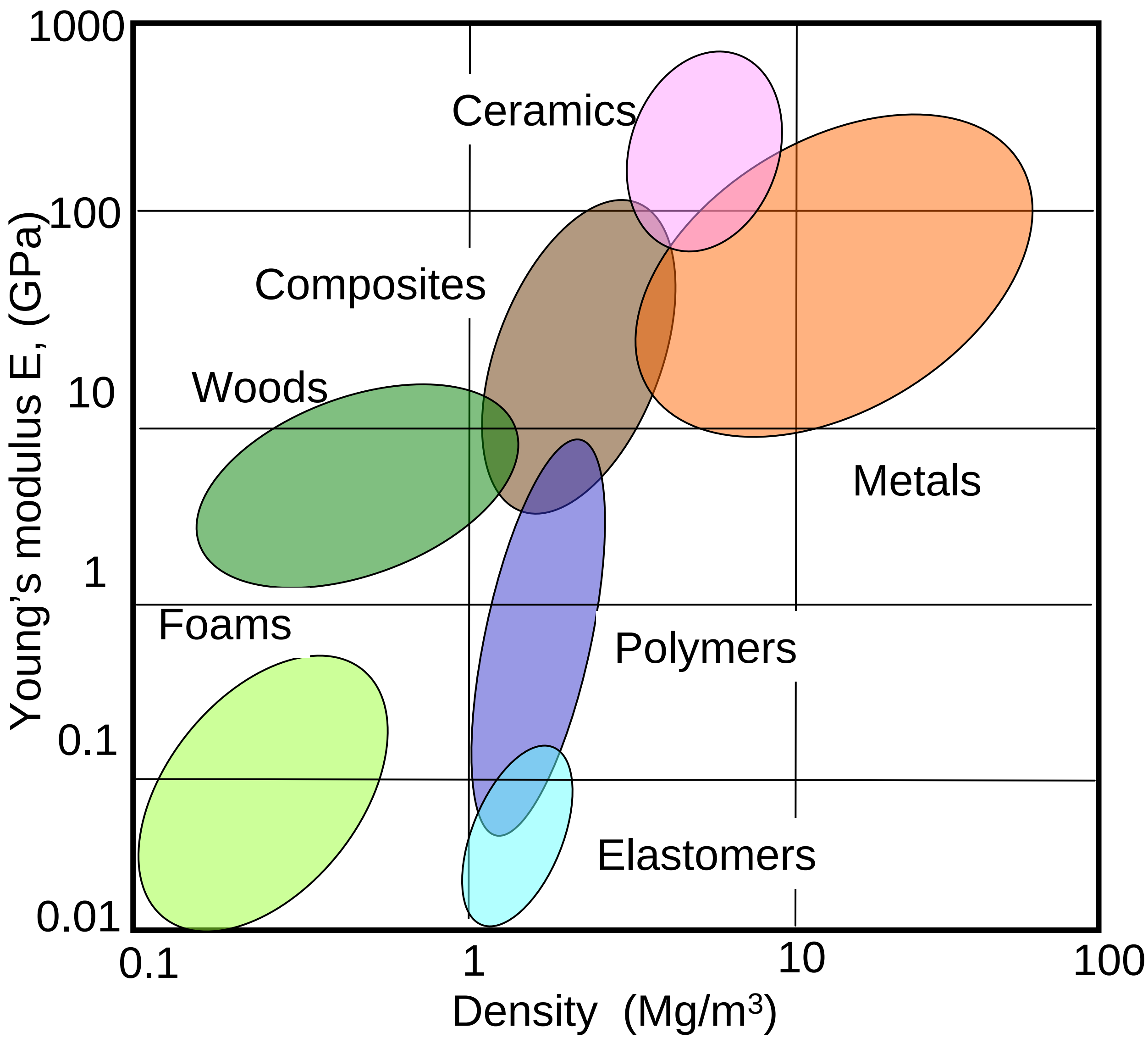


Bar- chart created with *CES 4* (Edu1)

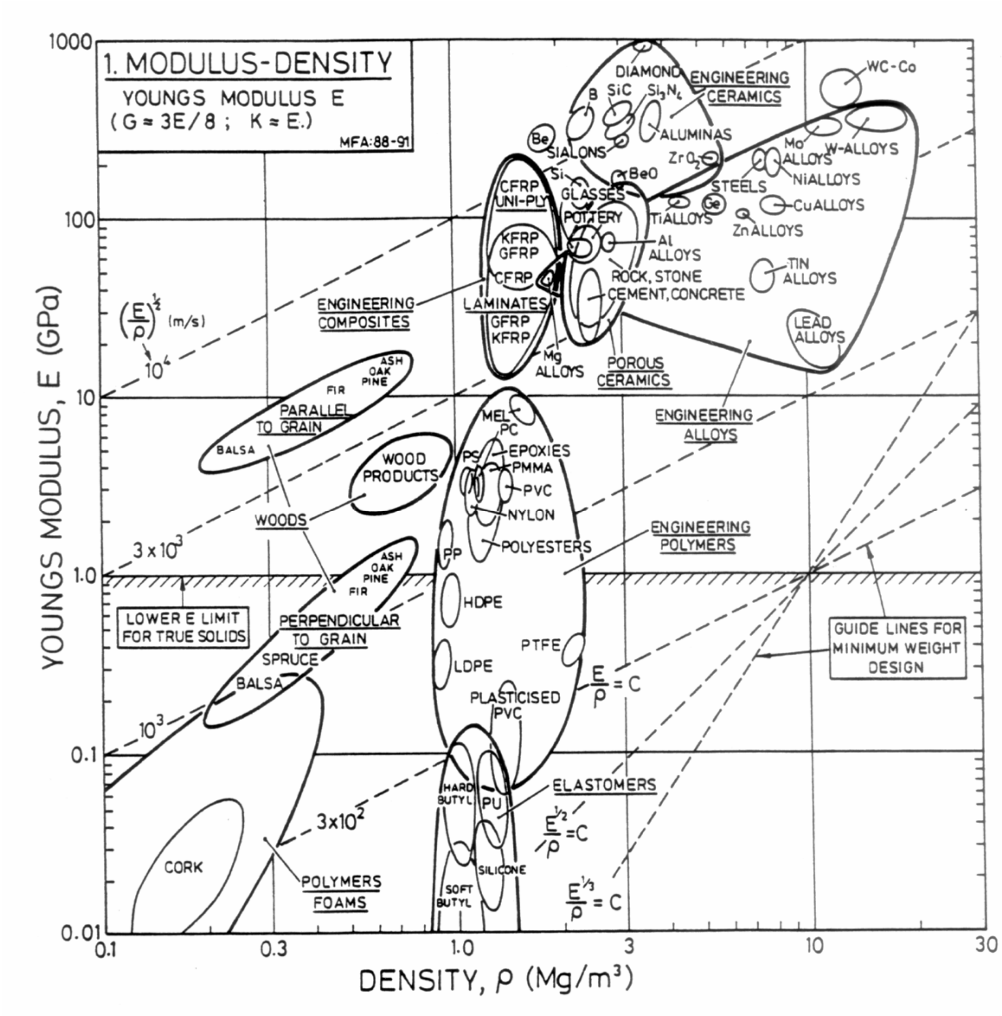


- Explore relationships
- Elementary selection ("Find materials with large elastic limit")

Material property- charts: Modulus - Density

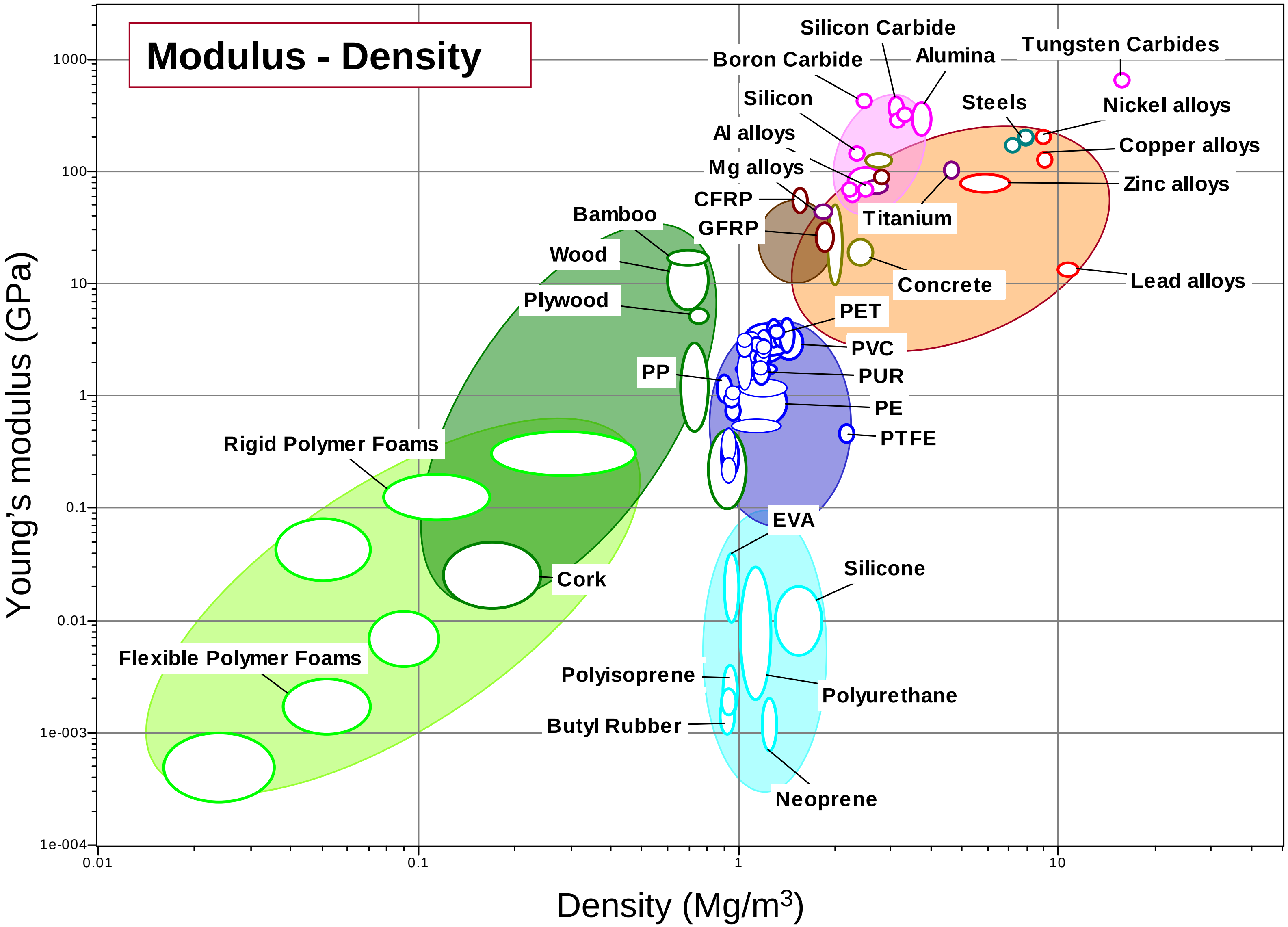


Hard-copy charts: Modulus - Density

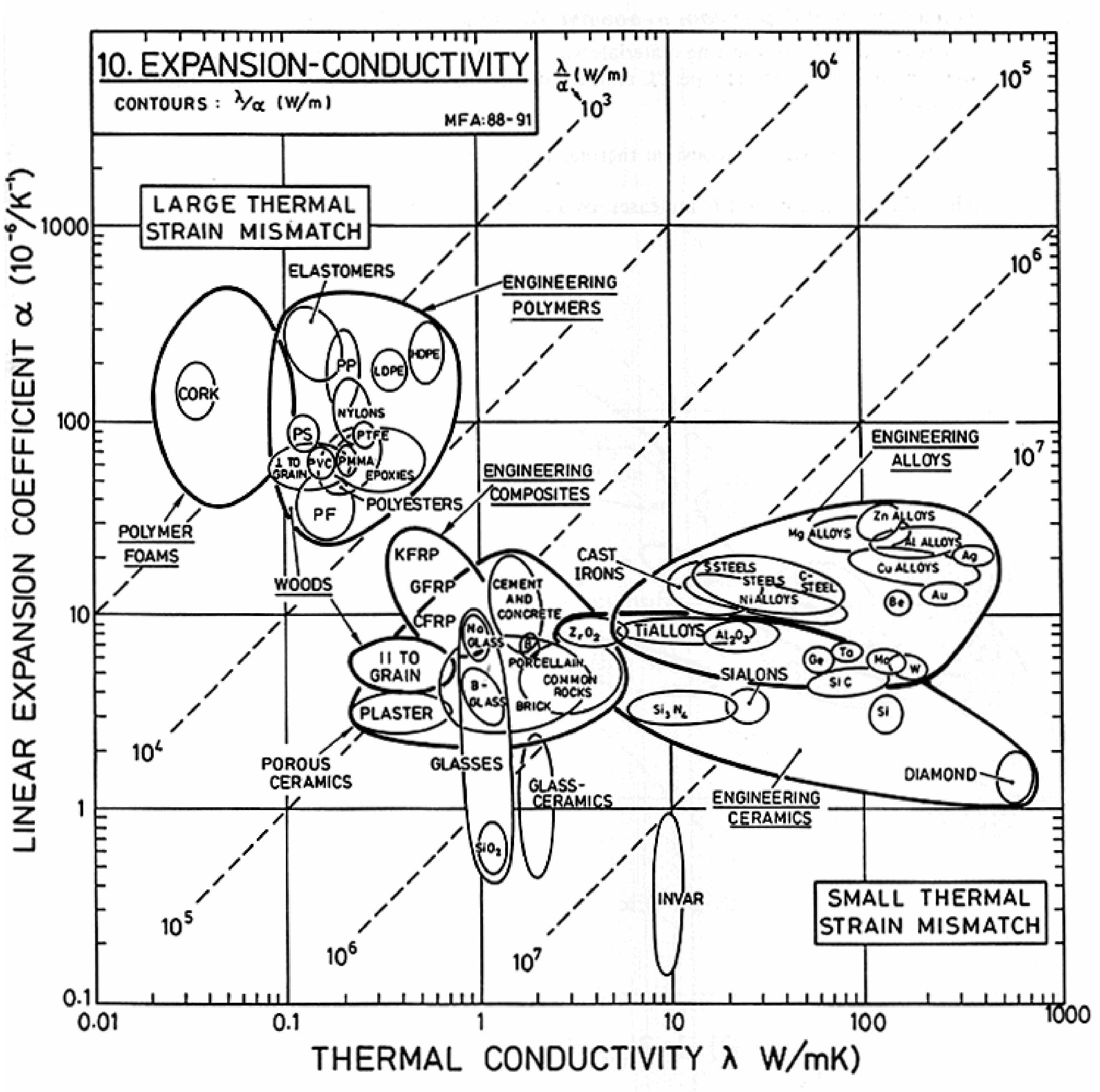


Hard-copy charts can be copied from MSMD, or downloaded from www.grantadesign.com

Property chart created with *CES 4, Level 1*



Hard-copy charts: T-expansion - T-conduction



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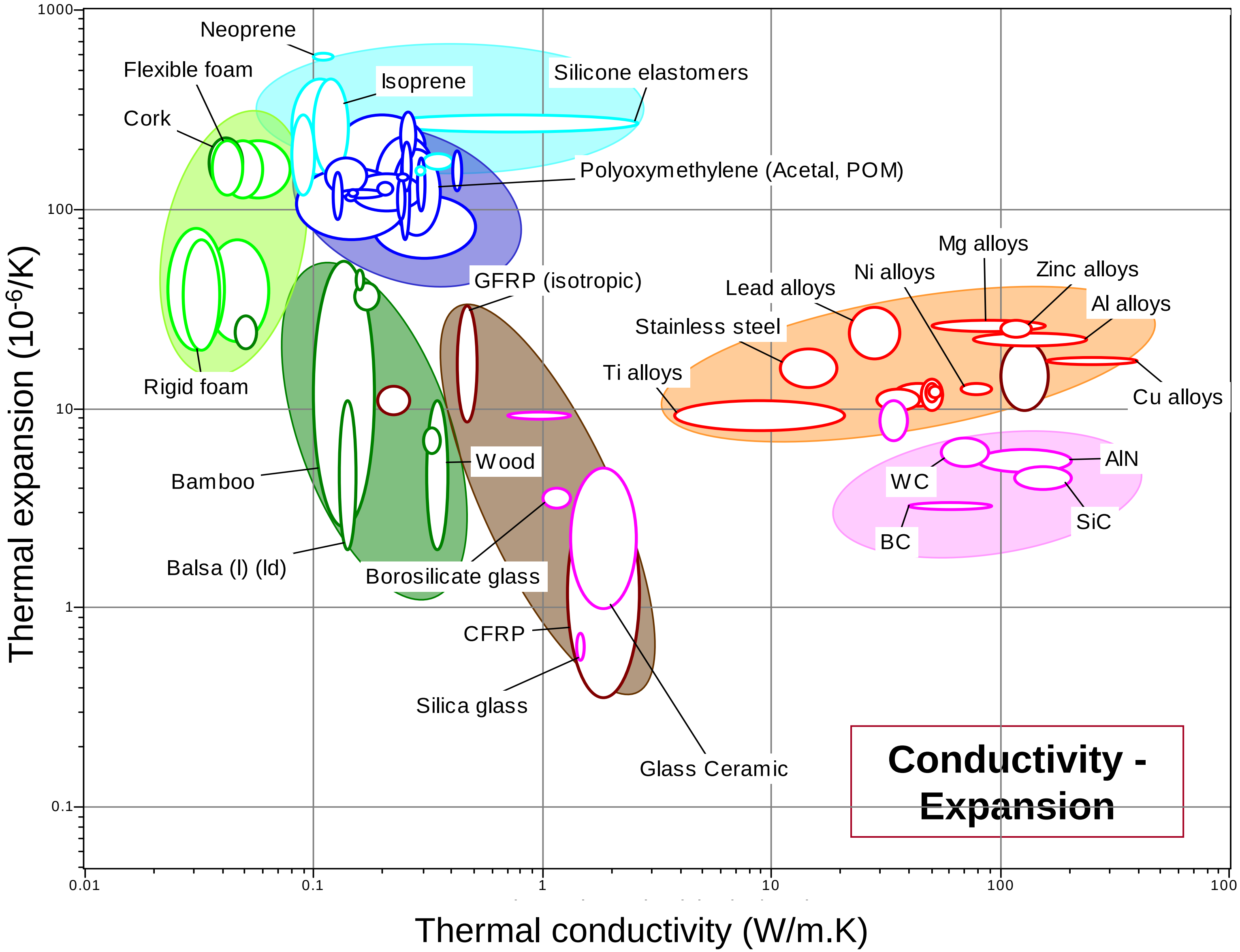
Property chart created with *CES 4*, *Level 1*



The main points

- A classification system for materials allows data for them to be organised
- The data takes several forms:

  (a) numeric, non-numeric data that can be structured in a uniform way for all materials

  (b) supporting information specific to a single material, best stored as text and images
- The organization allows information to be retrieved accurately and efficiently
- Visual presentation of data as bar-charts and property (bubble) charts reveals relationships and allows comparisons

Demo: creating bar and bubble charts with CES 4