School of Mechanical and Manufacturing Engineering

MMAN2130 Design and Manufacturing

Term 3 – 2019

Material Selection - Introduction

| Material Selection - Introduction|

Learning Outcomes: At the end of this week's presentation, you will have covered or understand:

- material cost drivers and availability
- appreciate the link between, design, process and material selection
- understand basic mechanical and physical properties of materials
- Understand the importance of materials and their properties
- learn the primary engineering materials

Externalities - Economics

"Externalities are the cost or benefits that affect a party who did not choose to accept or incur that cost or benefit."

Externalities Political– Rare earth materials (Neodinium,Iron/Boron)

China have large reserves of rare earths, but not all of them.

Rare earths go into almost every electrical device (cars, walkman)

What happened to rare earth materials around ~2006?

Externalities - Social

Social & Political & Environmental

Externalities – Social - Steel

1920's Mesabi range, high quality. USA super strong in steel.

What made the USA super strong in steel in 1945?

Abundance/availability (Ashby, 2010)

Crust		Oceans		Atmosphere	
Element	Weight %	Element	Weight %	Element	Weight %
Oxygen	47	Oxygen	85	Nitrogen	79
Silicon	27	Hydrogen	10	Oxygen	19
Aluminum	8	Chlorine	2	Argon	2
Iron	5	Sodium	1	Carbon dioxide	0.04
Calcium	4	Magnesium	0.1		
Sodium	3	Sulfur	0.1		
Potassium	3	Calcium	0.04		
Magnesium	2	Potassium	0.04		
Titanium	0.4	Bromine	0.007		
Hydrogen	0.1	Carbon	0.002		
Phosphorus	0.1				
Manganese	0.1				
Fluorine	0.06				
Barium	0.04				
Strontium	0.04				
Sulfur	0.03				
Carbon	0.02				

Energy content

Table 2.4 Approximate Energy Content of Materials (GJ ton^{-1})

Material	Energy
Aluminum	280
Plastics	85–180
Copper	140, rising to 300
Zinc	68
Steel	55
Glass	20
Cement	7
Brick	4
Timber	2.5–7
Gravel	0.2
Oil	44
Coal	29

Selection of **structural** materials

- Cost
- Strength/fracture resistance
- Availability
- Fabricability
- Recyclability
- Repairability.

Relative costs of materials

Table 2.1 Approximate Relative Price per Ton (mild steel = 100)

Material	Relative price
Platinum	12 m
Diamonds, industrial	10 m
Gold	9.6 m
Silver	290,000
CFRP (materials 70% of cost; fabrication 30% of cost)	20,000
Cobalt/tungsten carbide cermets	15,000
Tungsten	5000
Cobalt alloys	7000
Titanium alloys	2000
Nickel alloys	6000
Polyimides	8000
Silicon carbide (fine ceramic)	7000
Magnesium alloys	1000
Nylon 66	1500
Polycarbonate	1000
PMMA	700
Magnesia, MgO (fine ceramic)	3000
Alumina, Al_2O_3 (fine ceramic)	3000
Tool steel	500
GFRP (materials 60% of cost; fabrication 40% of cost)	1000
Stainless steels	600
Copper, worked (sheets, tubes, bars)	2000
Copper, ingots	2000
Aluminum alloys, worked (sheet, bars)	650
Aluminum ingots	550
Brass, worked (sheet, tubes, bars)	2000
Brass, ingots	2000
Epoxy	1000
Polyester	500
Glass	400
Foamed polymers	1000
Zinc, worked (sheet, tubes, bars)	550
Zinc, ingots	450
Lead, worked (bars, sheet, tube)	650
Lead, ingots	550
Natural rubber	300
Polypropylene	200
Polyethylene, high density	200
Polystyrene	250
Hard woods	250
Polyethylene, low density	200

Table 2.1 Cont'd

Material	Relative price
Polyvinyl chloride	300
Plywood	150
Low-alloy steels	200
Mild steel, worked (angles, sheet, bars)	100
Cast iron	90
Soft woods	50
Concrete, reinforced (beams, columns, slabs)	50
Fuel oil	190
Cement	20
Coal	20

Note: *At April 2011 mild steel was $500/ton*

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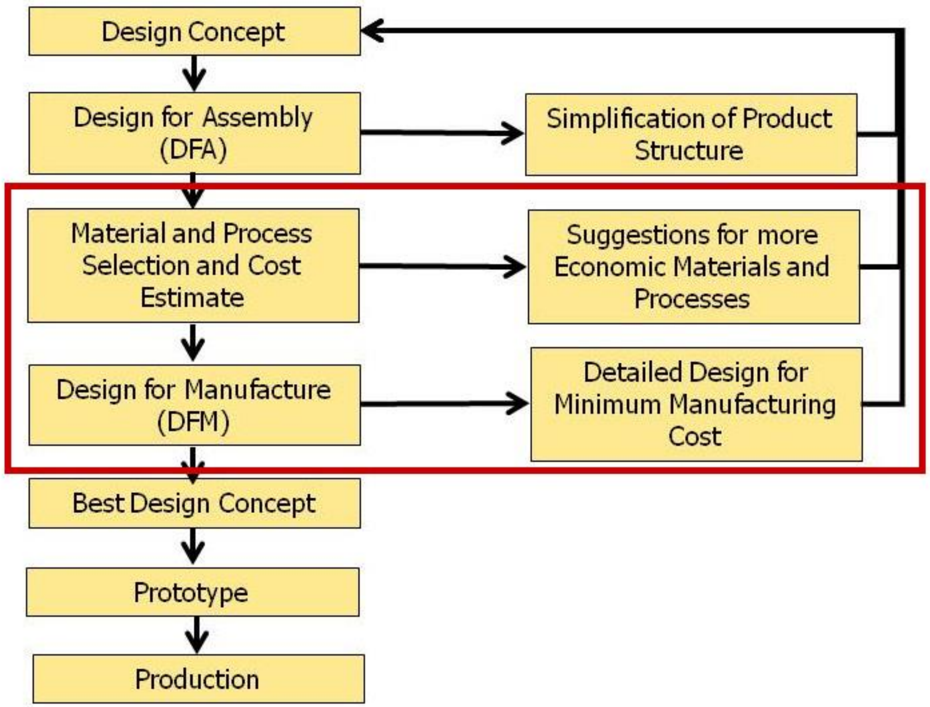
Product, Process Design and Materials Selection

- Material selection in design is a multi-criteria decision making



Materials in Design

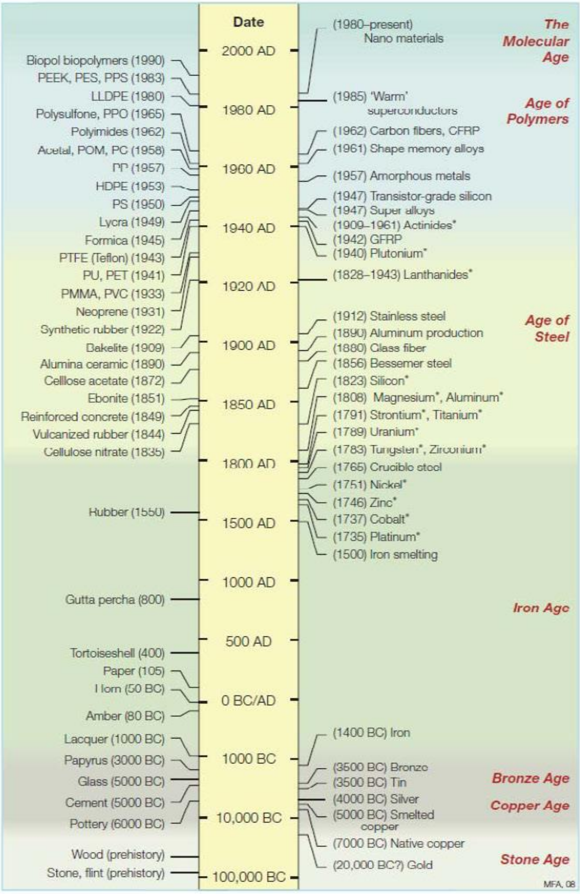
- Design is the process of translating a new idea or a market need into the detailed information from which a product can be manufactured

- Each of its stages requires decisions about the materials of which the product is to be made and the process for making it

Materials in Design

- Material development is driven by the desire for ever greater performance

- Today, over 160,000 materials are available to engineers



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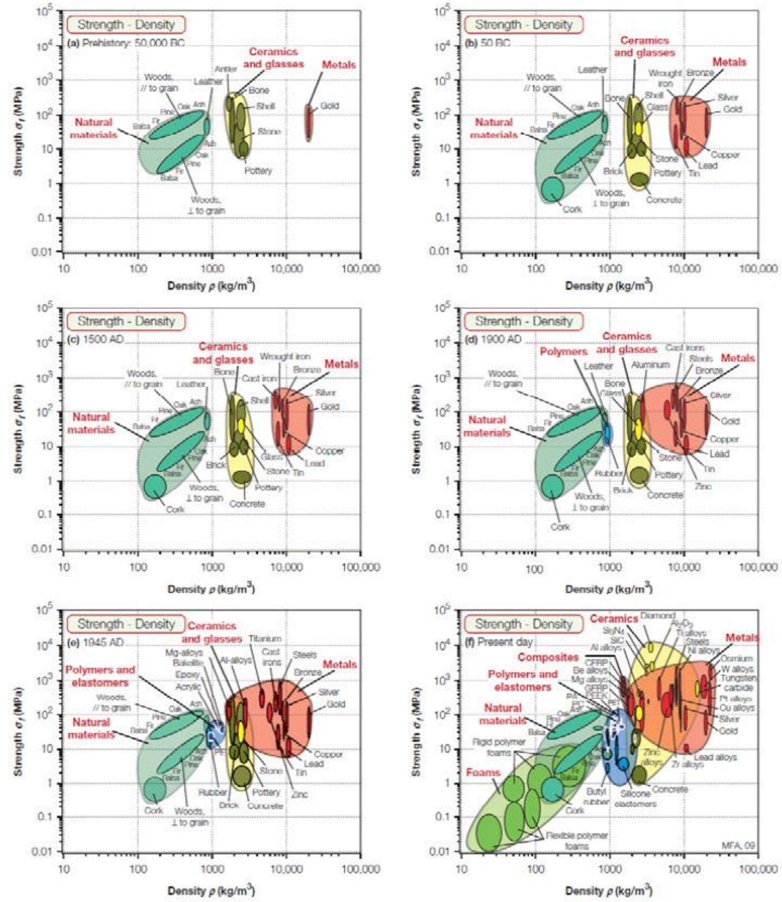
Materials in Design

- The development of materials to meet demands on strength and density is illustrated by these material property charts
- Similar time plots show this progressive filling for all materials properties



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Evolution of Materials in Products

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- Early kettles, heated directly over a fire, were made of materials that could conduct heat well and withstand exposure to an open flame
- Today almost all kettles are made of plastic, allowing economic manufacture with great freedom of form and color

Evolution of Materials in Products

- The development of vacuum cleaners has been rapid and driven by the use of new materials
- Hand-powered cleaners made mostly of natural materials have been replaced with high powered motors and centrifugal filtration

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Evolution of Materials in Products

- Early cameras were made of wood and constructed with the care and finish of a cabinetmaker; they had well-ground glass lenses manufactured by techniques developed for watch and clock making
- High end cameras now manufactured with the scientific instrument precision; lower end models are made with molded polypropylene or ABS bodies

Evolution of Materials in Products

- Early planes were made of low-density woods, steel wire, and silk
- The aluminum airframe provided high stiffness and strength to allow planes to be bigger and fly further
- The future of airframes is exemplified by Boeing's 787 Dreamliner (80% carbon-fiber reinforced plastic, claims to be 30% lighter per seat than competing aircraft

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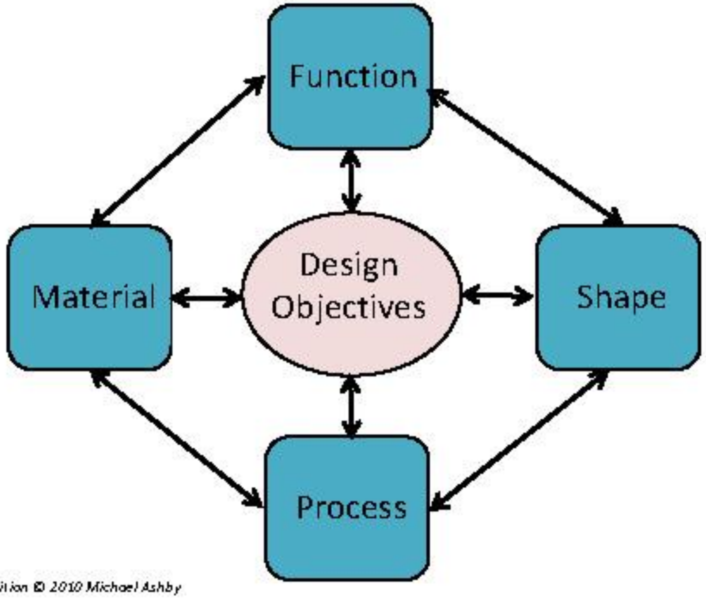
Material Selection Problem

- Interaction between function, material, process, and shape
- It is not necessarily a material, but a certain profile of properties – the one that best meets the needs of the design



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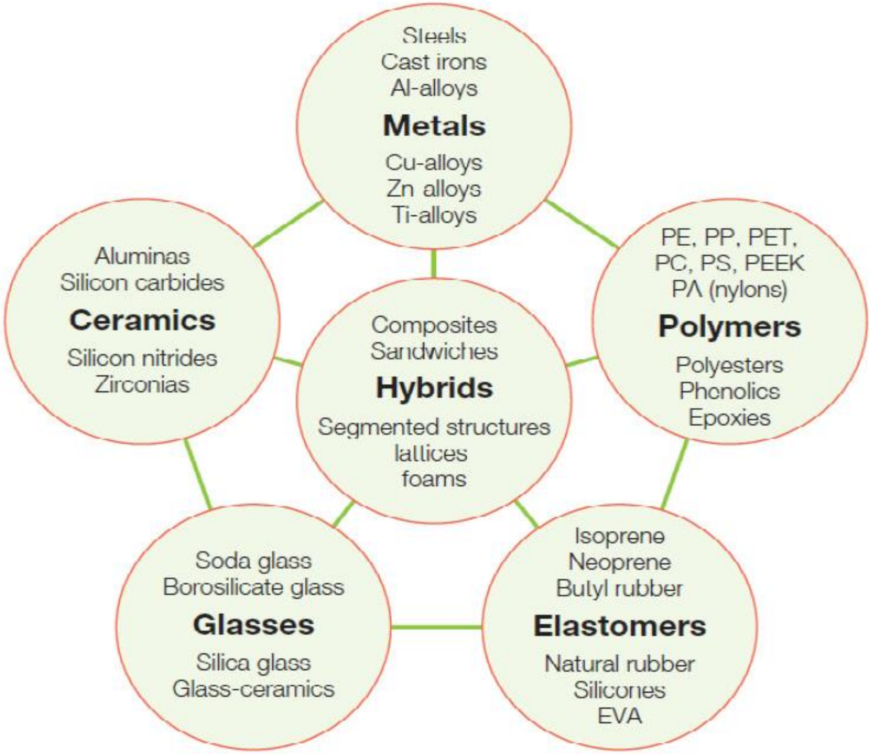
Menu of Engineering Materials

- The members of a material family have certain features in common: similar properties, similar processing routes, and, often, similar applications



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Menu of Engineering Materials

Ceramics

- Stiff – high E
- Hard
- Abrasion resistant
- Good high temperature strength
- Good corrosion resistance
- Brittle

Glasses

- Hard
- Corrosion resistant
- Electrically insulating
- Transparent
- Brittle

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Menu of Engineering Materials

Polymers

- Light – low ρ
- Easily shaped
- High strength/unit weight (σ/ρ)
- Lack stiffness – low E (50X less than metals)
- Properties highly sensitive to temperature

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Elastomers

- Lack stiffness – low E (500 – 5000X less than metals)
- Able to retain initial shape after being stretched
- Relatively strong and tough

Menu of Engineering Materials

Metals

- Tough – high K_{IC}
- Stiff – high E
- Ductile
- Wide range of strengths depending on composition and processing
- Thermally and electrically conductive
- Reactive – low corrosion resistance

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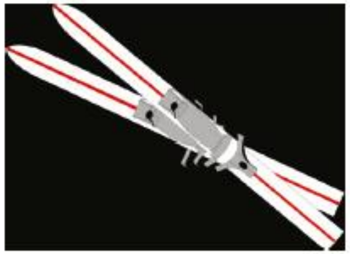

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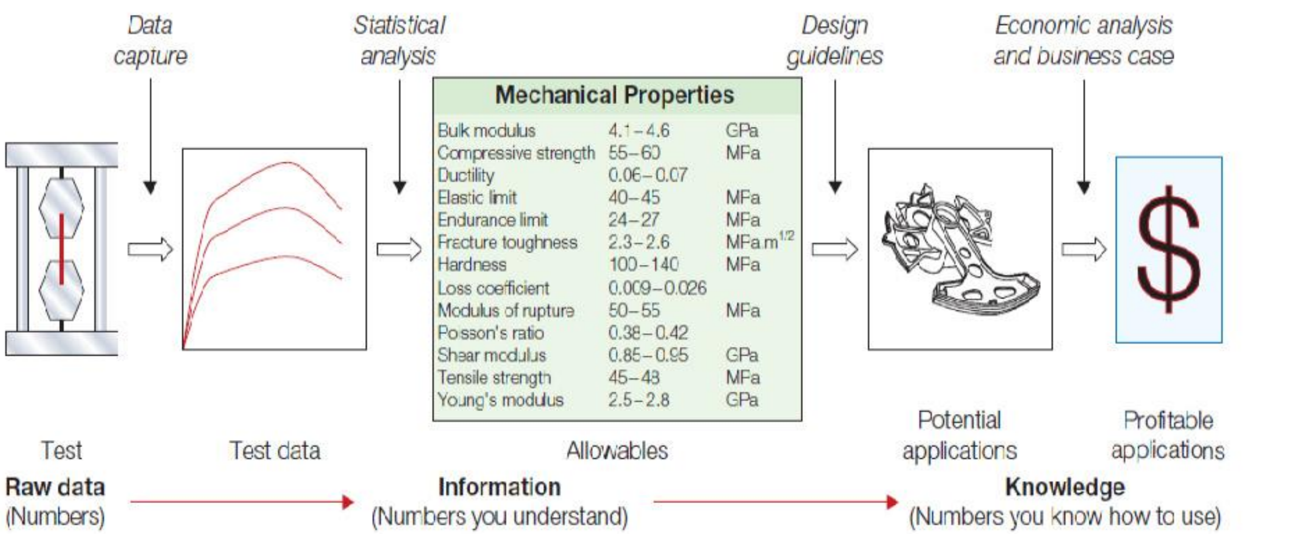
Hybrids

- Relatively strong and tough
- Expensive
- Difficult to shape and join
- Properties dependent on combination of materials

Type of Material Information needed in Design

- Interested in the data in the center of the schematic; structured data for design allowables and information concerning the materials ability to be formed, joined, and finished



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Type of Material Information needed in Design

- Each material can be thought of as having a set of attributes or properties

- The combination that characterizes a given material is its property profile

Class	Property	Symbol and Units
General	Density	ρ (kg/m^3 or Mg/m^3)
	Price	C_m ($/kg)
Mechanical	Elastic moduli (Young's, shear, bulk)	E, G, K (GPa)
	Yield strength	σ_y (MPa)
	Tensile (ultimate) strength	σ_{ts} (MPa)
	Compressive strength	σ_c (MPa)
	Failure strength	σ_f (MPa)
	Hardness	H *(Vickers)*
	Elongation	ε (–)
	Fatigue endurance limit	σ_e (MPa)
	Fracture toughness	K_{1c} (MPa.m$^{1/2}$)
	Toughness	G_{1c} (kJ/m^2)
	Loss coefficient (damping capacity)	η (–)
	Wear rate (Archard) constant	K_AMPa^{-1}
Thermal	Melting point	T_m (°C or K)
	Glass temperature	T_g (°C or K)
	Maximum service temperature	T_{max} (°C or K)
	Minimum service temperature	T_{min} (°C or K)
	Thermal conductivity	λ (W/m.K)
	Specific heat	C_p (J/kg.K)
	Thermal expansion coefficient	α (K^{-1})
	Thermal shock resistance	ΔT_s (°C or K)
Electrical	Electrical resistivity	ρ_e (Ω.m or $\mu\Omega$.cm)
	Dielectric constant	ε_r (–)
	Breakdown potential	V_b (10^6 V/m)
	Power factor	P (–)
Optical	Refractive index	n (–)
Eco-properties	Embodied energy	H_m (MJ/kg)
	Carbon footprint	CO_2 (kg/kg)

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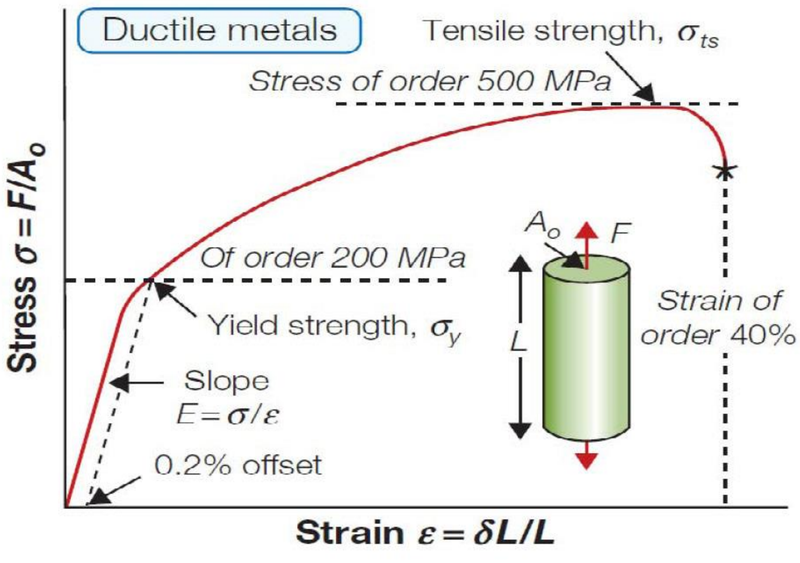
Mechanical Properties

- The stress-strain curve for a metal, showing the modulus, E, the 0.2% yield strength, σ_y, and the ultimate strength, σ_{ts}

- The strain at the point of failure indicates the ductility of a material



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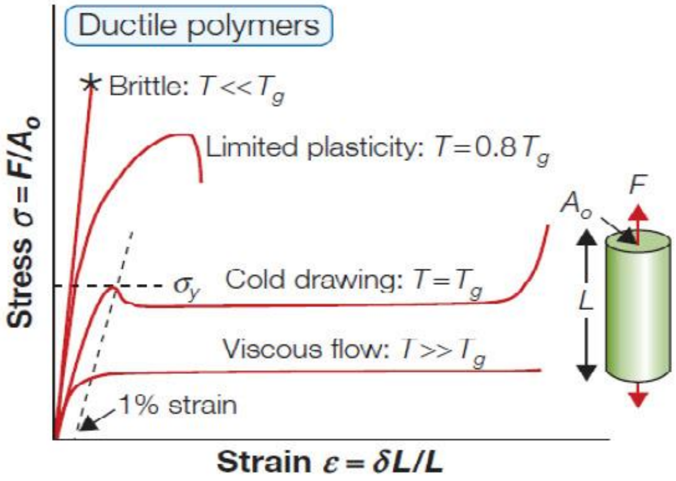
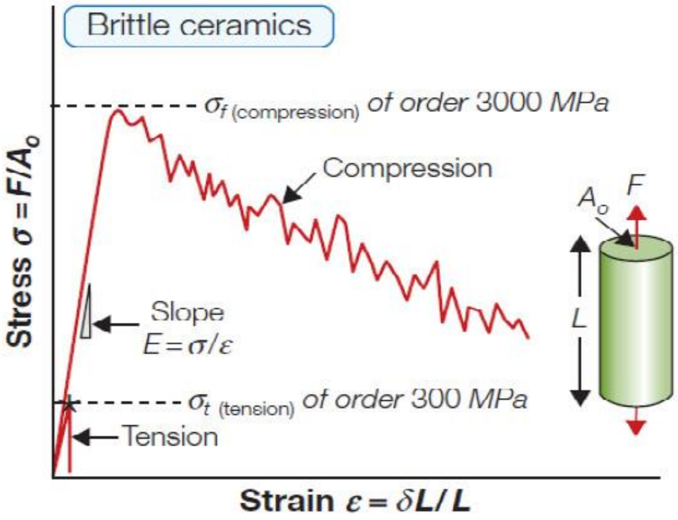
Mechanical Properties



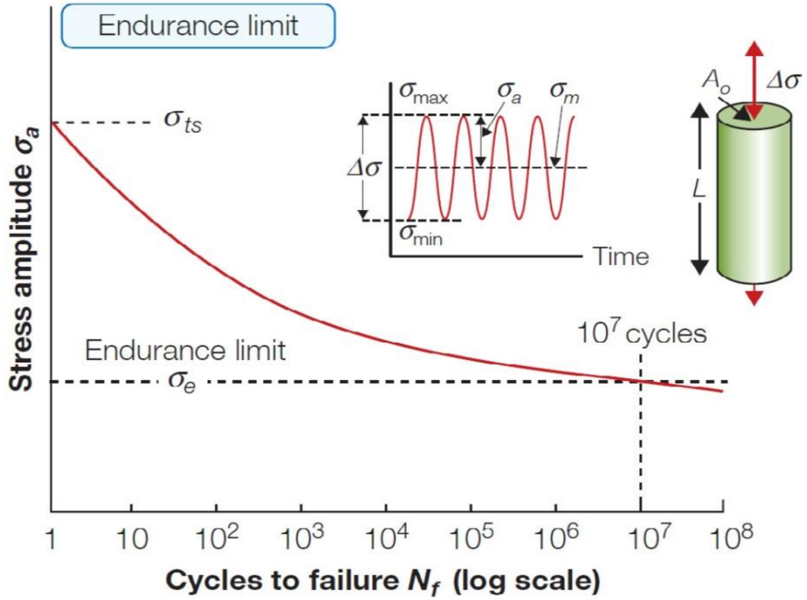


- The tensile response of a polymer varies with temperature – here the response is shown with respect to the glass transition temperature, T_g

- The compressive strength of a ceramic is 10-15 times greater than the tensile strength

Mechanical Properties

- For many materials there exists a fatigue or *endurance limit*, σ_e, illustrated by the $\Delta\sigma - N_f$ curve.
- It is the stress amplitude below which fracture does not occur, or only occurs after a very large number ($N_f > 10_7$) cycles



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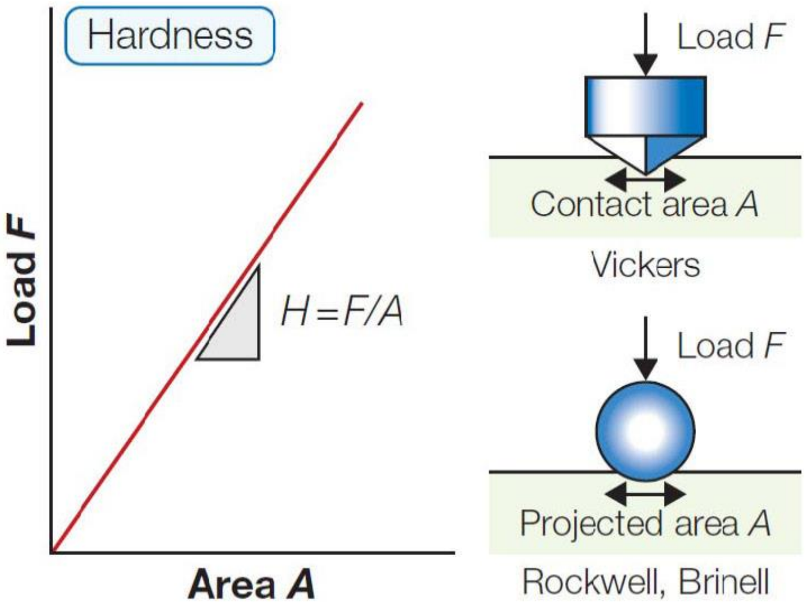
Mechanical Properties

- Hardness is measured as the load, *F*, divided by the projected area of contact, *A*, when a diamond-shaped indenter is forced into the surface



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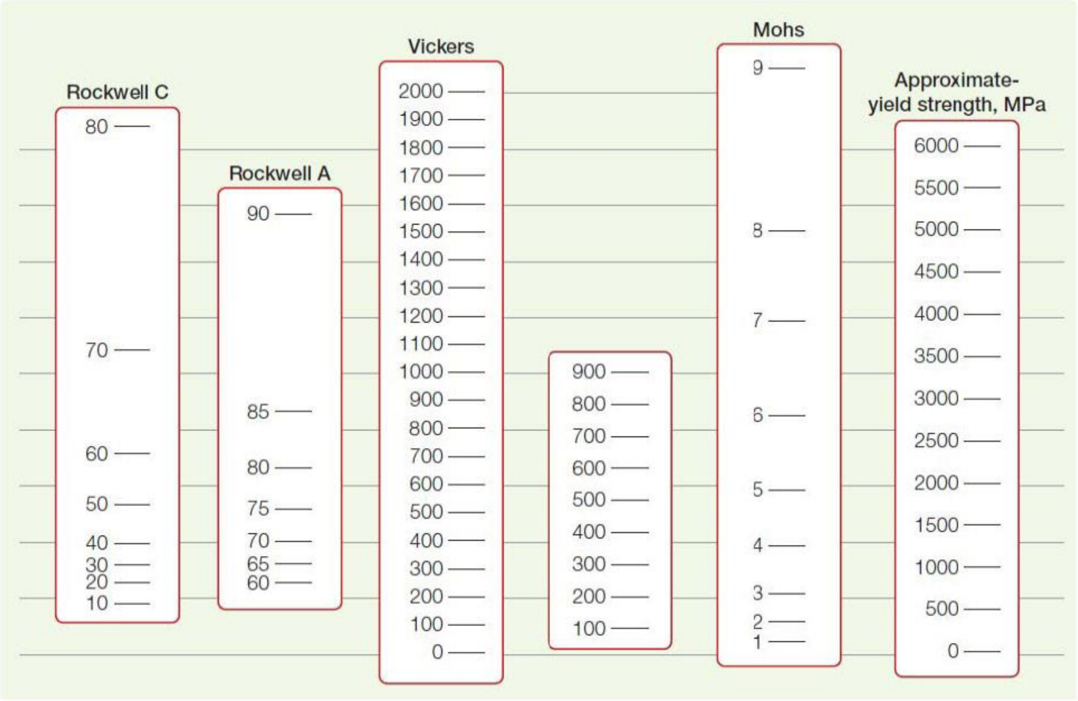
Mechanical Properties

- Commonly used hardness scales and related to each other



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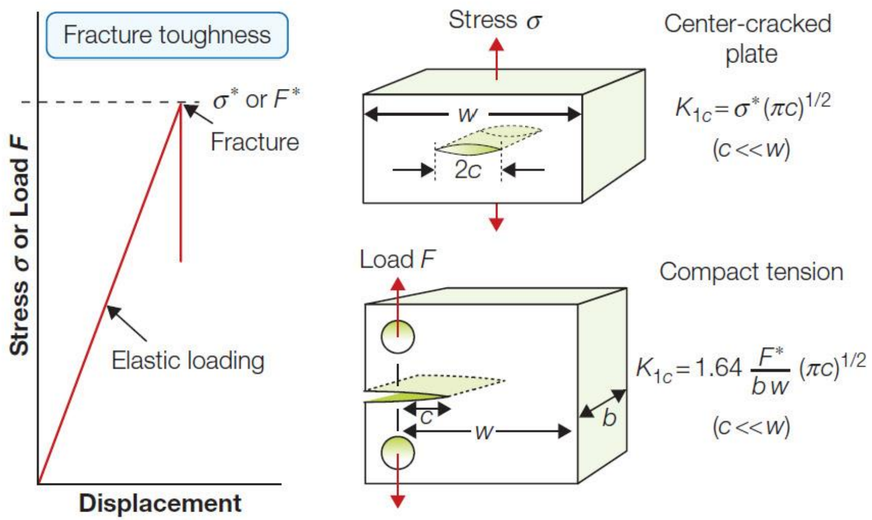
Mechanical Properties

- The fracture toughness, K_{IC}, measures the resistance to the propagation of a crack;
- The test specimen containing a crack of length 2c fails at stress σ^*; the fracture toughness is then $K_{IC} = Y\sigma^*(\pi c)^{1/2}$



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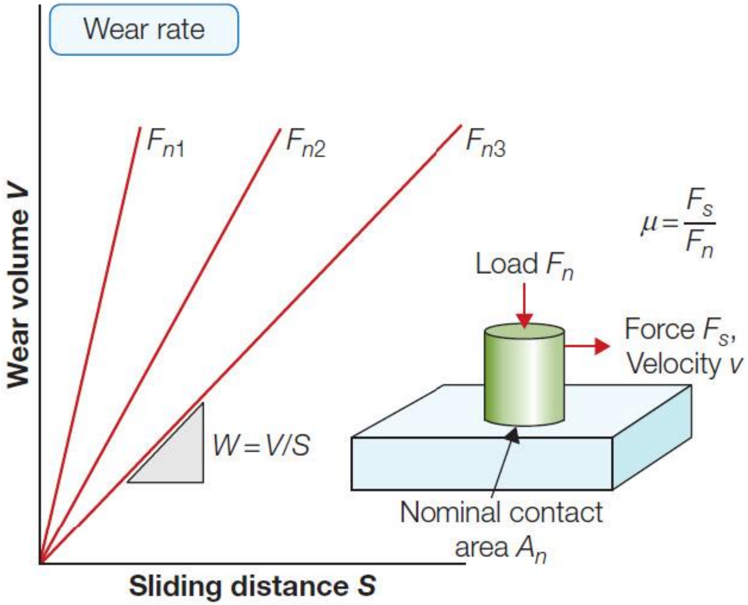
Mechanical Properties

- Wear is the loss of material from surfaces when they slide;

- The wear resistance is measured by the Archard wear constant, K_A



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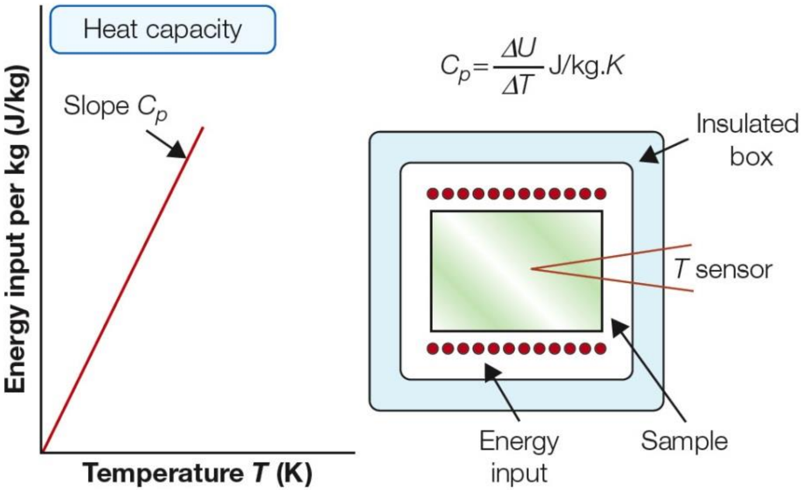
Thermal Properties

- *The heat capacity* – the energy to raise the temperature of 1 kg of material by 1°C



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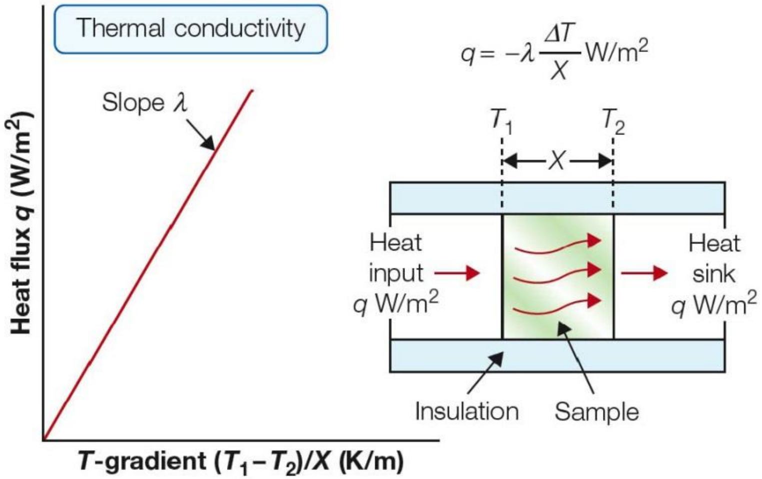
Thermal Properties

- The thermal conductivity λ measures the flux of heat driven by a temperature gradient



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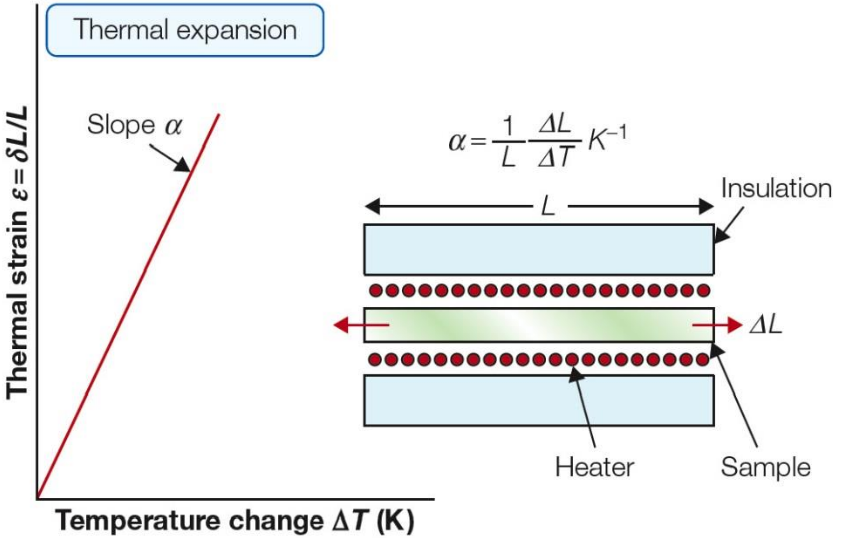
Thermal Properties

- The linear-thermal expansion coefficient α measures the change in length, per unit length, when the sample is heated



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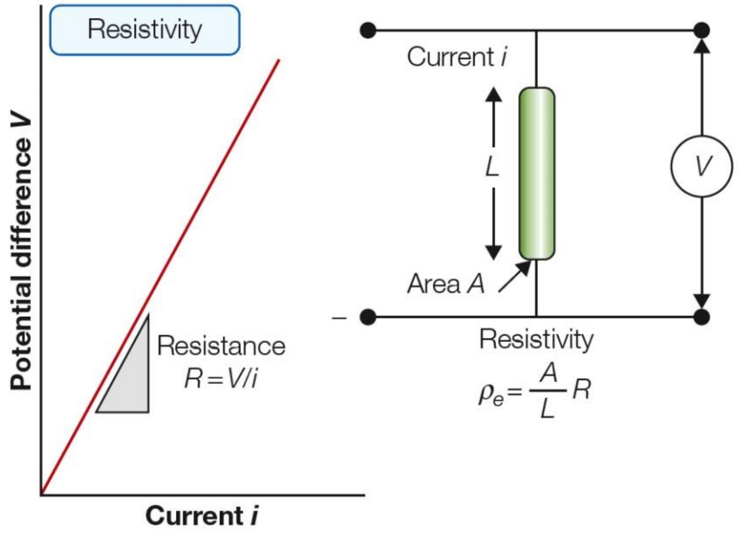
Electrical Properties

- Electrical resistivity, ρ_e, is measured as the potential gradient, *V/L*, divided by the current density, *i/A*;
- It is related to the resistance, *R*, by $\rho_e = AR/L$



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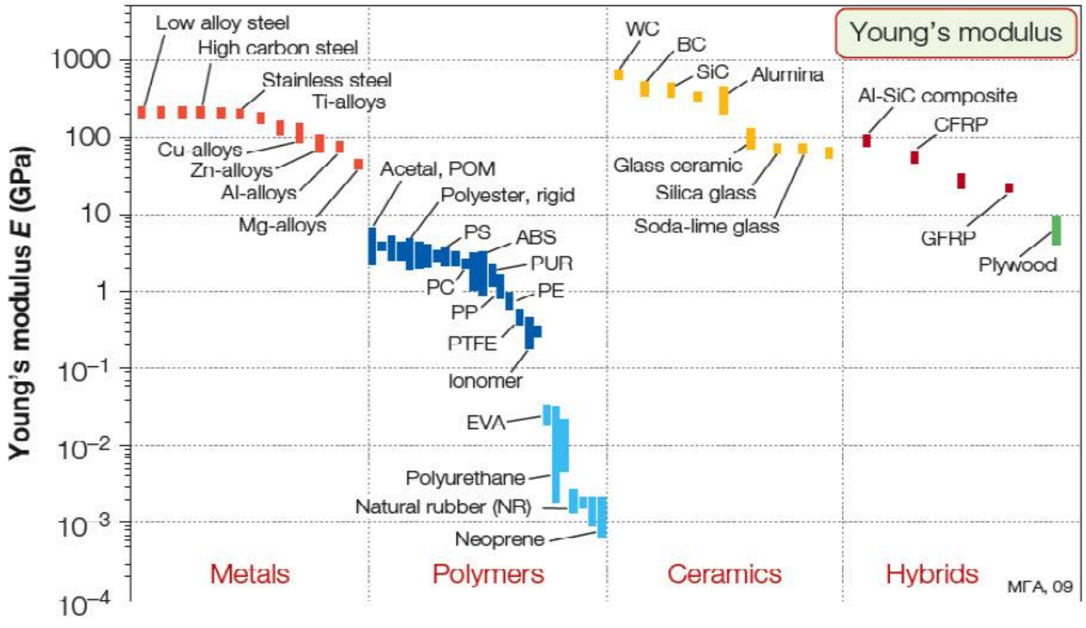
Bar Charts: One property

- Each property of an engineering material has a characteristic range of values; the bar chart shows the modulus for a family of solids



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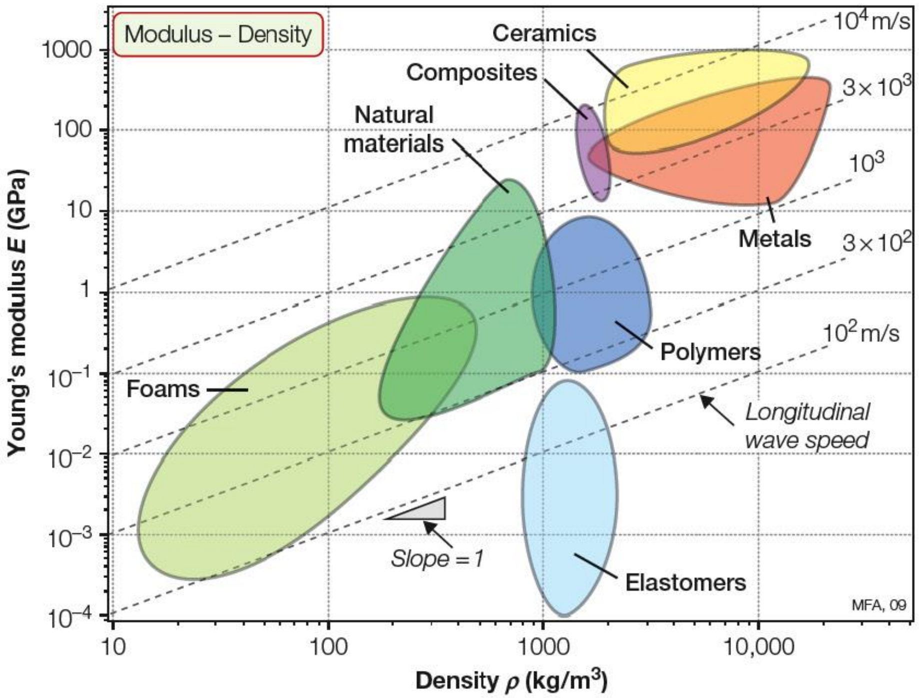
Comparing Multiple Properties

- Young's modulus plotted against density on log scales; each material class occupies a characteristic field



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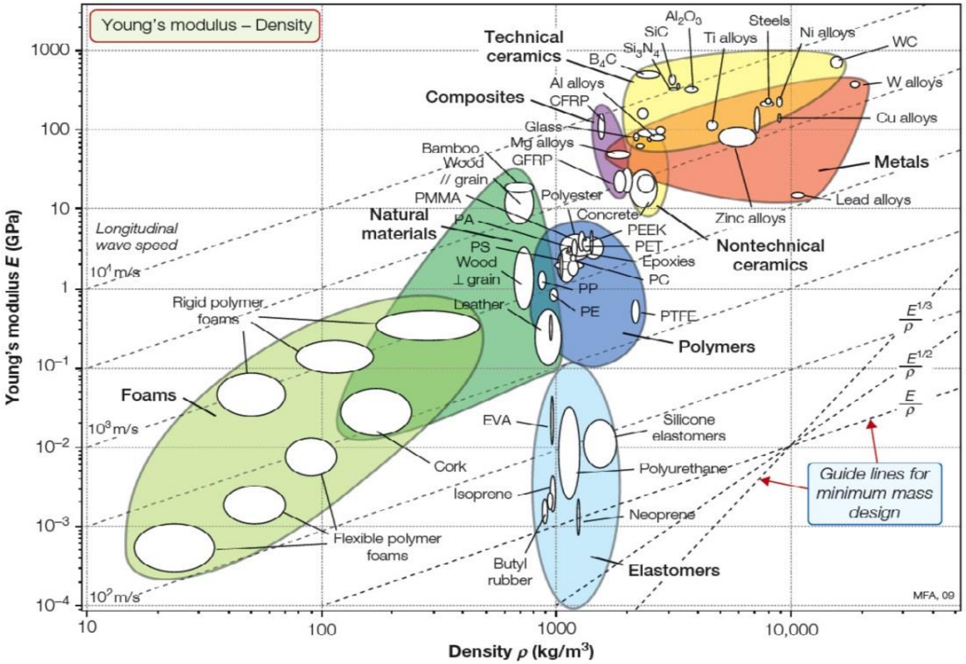
Young's Modulus: Density

- The guide lines of constant E/ρ, $E^{1/2}/\rho$, and $E^{1/3}/\rho$ allow selection of materials for minimum weight, deflection-limited, design



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Primary Engineering Materials

Family	Classes	Short Name
Metals (the metals and alloys of engineering)	Aluminum alloys	Al alloys
	Copper alloys	Cu alloys
	Lead alloys	Lead alloys
	Magnesium alloys	Mg alloys
	Nickel alloys	Ni alloys
	Carbon steels	Steels
	Stainless steels	Stainless steels
	Tin alloys	Tin alloys
	Titanium alloys	Ti alloys
	Tungsten alloys	W alloys
	Lead alloys	Pb alloys
	Zinc alloys	Zn alloys
Ceramics, *technical ceramics* (fine ceramics capable of load-bearing application)	Alumina	Al_2O_3
	Aluminum nitride	AlN
	Boron carbide	B_4C
	Silicon carbide	SiC
	Silicon nitride	Si_3N_4
	Tungsten carbide	WC
Ceramics, *nontechnical ceramics* (porous ceramics of construction)	Brick	Brick
	Concrete	Concrete
Glasses	Soda-lime glass	Soda-lime glass
	Borosilicate glass	Borosilicate glass
	Silica glass	Silica glass
	Glass ceramic	Glass ceramic

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Family	Classes	Short Name
Polymers (the thermoplastics and thermosets of engineering)	Acrylonitrile butadiene styrene	ABS
	Cellulose polymers	CA
	Ionomers	Ionomers
	Epoxies	Epoxy
	Phenolics	Phenolics
	Polyamides (nylons)	PA
	Polycarbonate	PC
	Polyesters	Polyester
	Polyetheretherkeytone	PEEK
	Polyethylene	PE
	Polyethylene terephthalate	PET or PETE
	Polymethylmethacrylate	PMMA
	Polyoxymethylene (Acetal)	POM
	Polypropylene	PP
	Polystyrene	PS
	Polytetrafluorethylene	PTFE
	Polyvinylchloride	PVC
Elastomers (engineering rubbers, natural and synthetic)	Butyl rubber	Butyl rubber
	EVA	EVA
	Isoprene	Isoprene
	Natural rubber	Natural rubber
	Polychloroprene (Neoprene)	Neoprene
	Polyurethane	PU
	Silicone elastomers	Silicones
Hybrids: composites	Carbon-fiber–reinforced polymers	CFRP
	Glass-fiber–reinforced polymers	GFRP
	SiC-reinforced aluminum	Al-SiC
Hybrids: foams	Flexible polymer foams	Flexible foams
	Rigid polymer foams	Rigid foams
Hybrids: natural materials	Cork	Cork
	Bamboo	Bamboo
	Wood	Wood

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Concluding Remarks

- Discussed the coupling of design, process, material selection
- Looked into evolution of materials in product design
- Briefly discussed the mechanical and physical properties of materials
- Next lecture will look into how to select materials with respect to function and processes