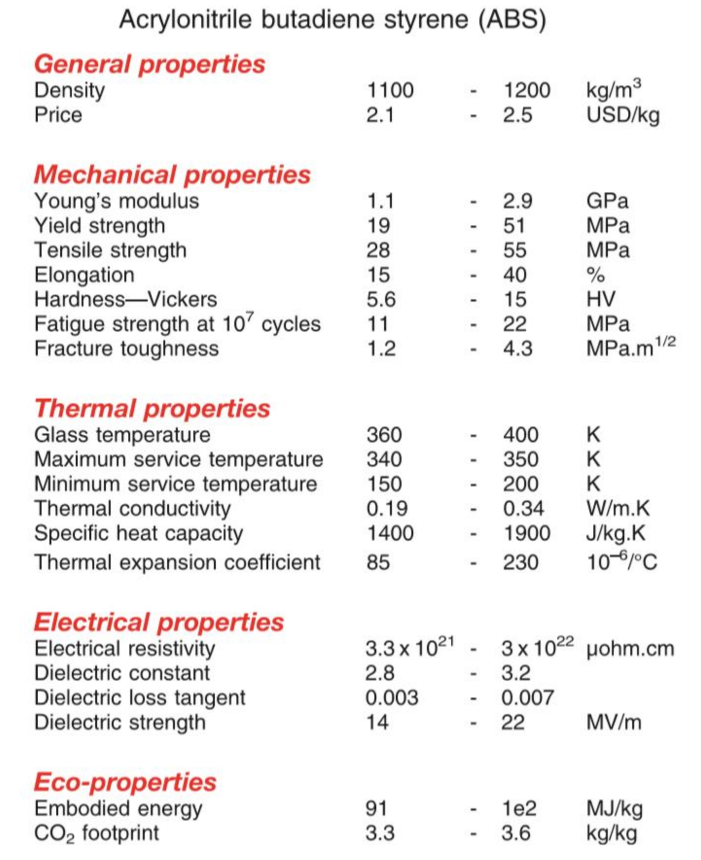
Materials Selection and Design

Materials Selection - Theory

Mechanical design process results with the selection of a material using a set of functional and geometrical constraints

A profile of properties is listed that fulfills the criteria set by these constraints that are required for the design to function adequately

Properties of all kinds of materials are documented in materials databases for the designer to find the one special material that best meets the needs of the design



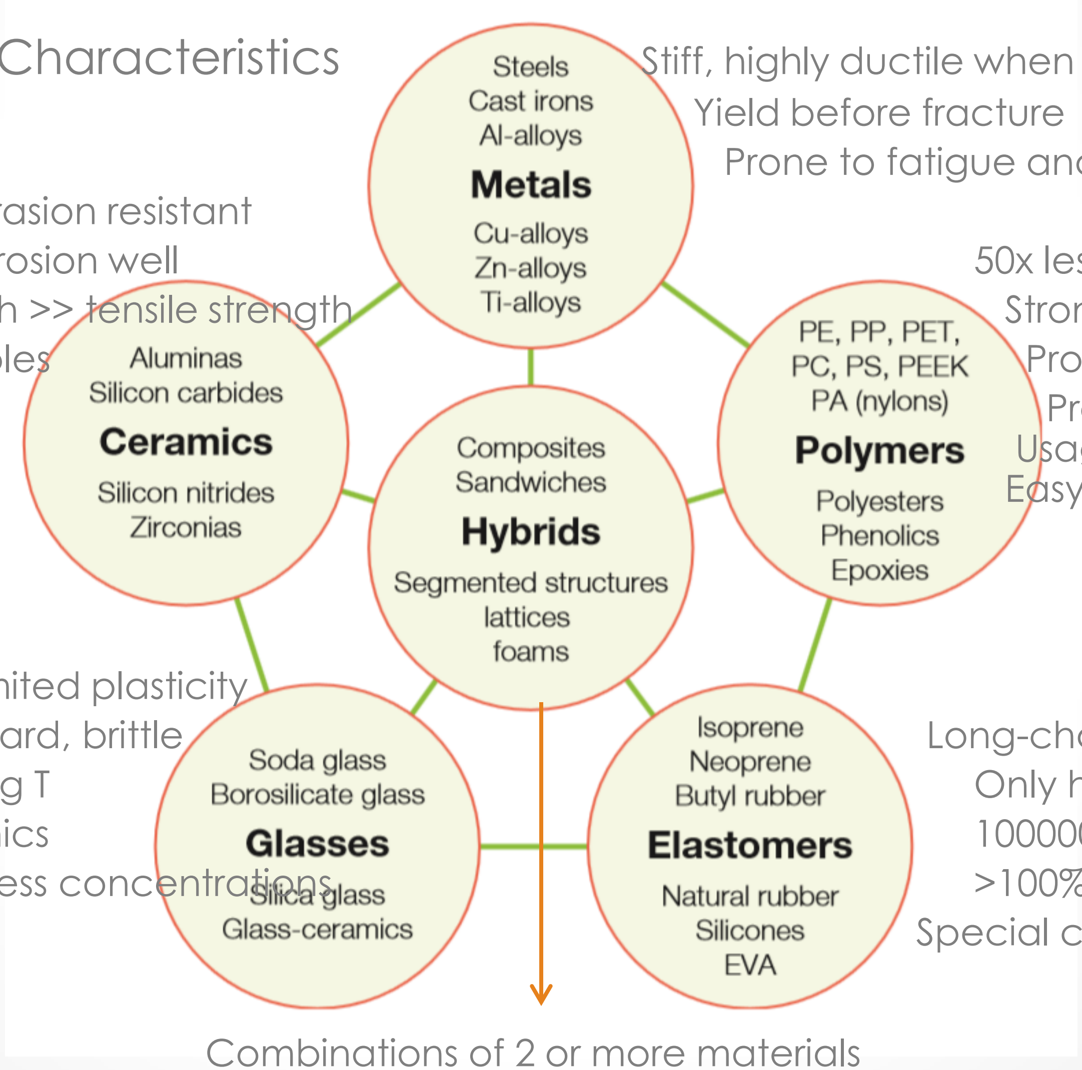
Acrylonitrile butadiene styrene (ABS)

General properties				
Density	1100	-	1200	kg/m^3
Price	2.1	-	2.5	USD/kg
Mechanical properties				
Young's modulus	1.1	-	2.9	GPa
Yield strength	19	-	51	MPa
Tensile strength	28	-	55	MPa
Elongation	15	-	40	%
Hardness—Vickers	5.6	-	15	HV
Fatigue strength at 10^7 cycles	11	-	22	MPa
Fracture toughness	1.2	-	4.3	MPa.m$^{1/2}$
Thermal properties				
Glass temperature	360	-	400	K
Maximum service temperature	340	-	350	K
Minimum service temperature	150	-	200	K
Thermal conductivity	0.19	-	0.34	W/m.K
Specific heat capacity	1400	-	1900	J/kg.K
Thermal expansion coefficient	85	-	230	10^{-6}/°C
Electrical properties				
Electrical resistivity	3.3×10^{21}	-	3×10^{22}	µohm.cm
Dielectric constant	2.8	-	3.2	
Dielectric loss tangent	0.003	-	0.007	
Dielectric strength	14	-	22	MV/m
Eco-properties				
Embodied energy	91	-	1e2	MJ/kg
CO_2 footprint	3.3	-	3.6	kg/kg

6 distinct material families

Each family has certain features like properties, processing routes, applications i
common

Subgroups and Characteristics



Stiff, highly ductile when pure
Yield before fracture
Prone to fatigue and corrosion

Stiff, brittle, hard, abrasion resistant
Resist high T and corrosion well
Compression strength >> tensile strength
Low tolerance for holes

50x less stiff than metals
Strong due to straining
Prone to creep
Properties vary with T
Usage limited to T < 250 C
Easy to shape, finish, color

Amorphous solids, limited plasticity
Moderate stiffness, hard, brittle
Have lower operating T
compared to ceramics
Low tolerance for stress concentrations

Long-chain polymers above T_g
Only have covalent bonds
100000x less stiff than metals
>100% straining
Special characterization tests

Combinations of 2 or more materials
Attractive properties combined, drawback avoided
Expensive, difficult to form and join

Gathering the materials information

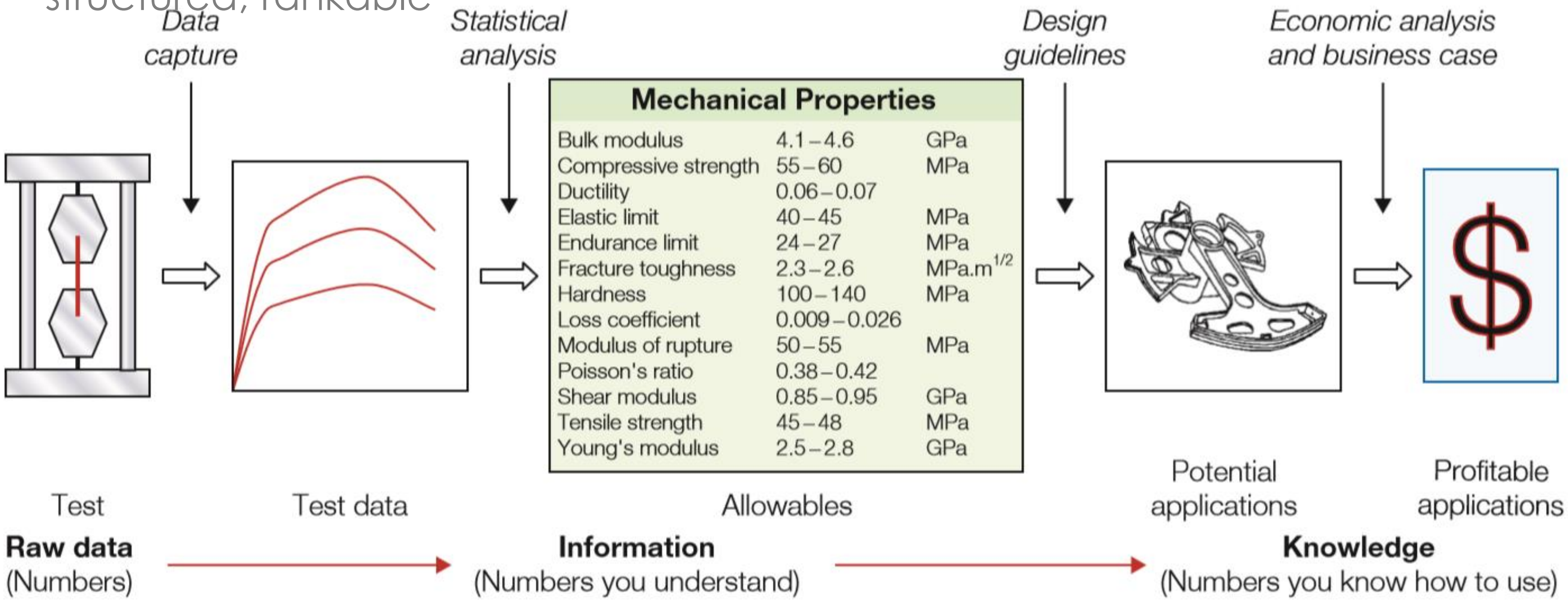
Engineers select materials conservatively due to the lack of confidence in new materials

Data for new, emerging materials may be incomplete or untrustworthy

Old, well-tried materials have established, reliable and easily found data

Yet innovation is often made possible by new materials

Data quality is important – Properties in data sheet should be guaranteed, structured, rankable



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

Structured properties enable engineers rank the candidate materials and filter them with respect to the desired properties

More information on each qualified material is needed as the material pool narrows

This supporting information or documentation of a material includes:

All its strengths

All its weaknesses

Possible processes to shape it

Possible processes to join it

Application history

Failure analysis

Supporting information is documented in handbooks, design guidelines, failure analyses, case studies

Certain parts may be available for one material and may not be available for another

Acrylonitrile butadiene styrene (ABS)

The material

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. The picture shows that ABS allows detailed moldings, accepts color well, and is nontoxic and tough enough to survive the worst that children can do.

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.

Tradenames

Claradex, Comalloy, Cycogel, Cycolac, Hanalac, Lastilac, Lupos, Lustran ABS, Magnum, Multibase, Novodur, Polyfabs, Polylac, Porene, Ronfalin, Sinkral, Terluran, Toyolac, Tufrex, Ultrastyr.

Material uses are subject to standards and codes which refer to material classes or subclasses

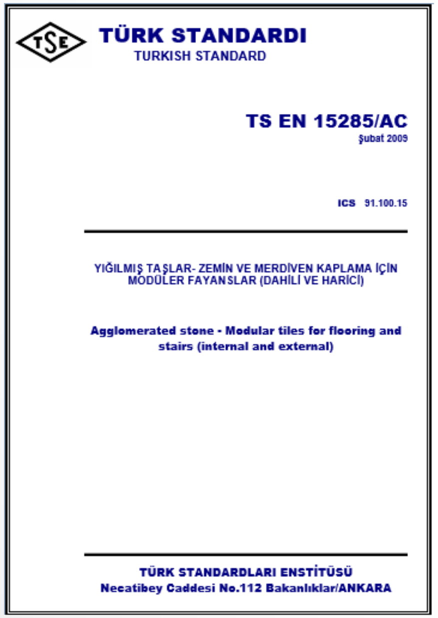
For a material to be used in contact with food, drug, or biological environment, it must have FDA approval

Metals and composites to be used in US military aircraft must have military approval

Most commercially produced metals in Turkey conform to TSE standards

Most commercially produced conventional whiteware goods conform to TSE standards

To qualify for best-practice design for the environment, material usage must conform to ISO 14040 guidelines



TÜRK STANDARDI
TURKISH STANDARD

TS EN 15285/AC
Şubat 2009

ICS 91.100.15

YIĞILMIŞ TAŞLAR- ZEMİN VE MERDİVEN KAPLAMA İÇİN MODÜLER FAYANSLAR (DAHİLİ VE HARİCİ)

Agglomerated stone - Modular tiles for flooring and stairs (internal and external)

TÜRK STANDARDLARI ENSTİTÜSÜ
Necatibey Caddesi No.112 Bakanlıklar/ANKARA

TÜRK STANDARDI
TURKISH STANDARD

TS EN 3896
Kasım 2002

1.Baskı

ICS 49.025.10

HAVACILIK SERİSİ-ÇELİK FE-WM 1501 (X13CRNİMOCO 12-3-2-2) -KAYNAK İÇİN DOLGU METALİ

Aerospace series - Steel FE-WM1501 (X13CrNiMoCo12-3-2-2) - Filler metal for welding

TÜRK STANDARDLARI ENSTİTÜSÜ
Necatibey Caddesi No.112 Bakanlıklar/ANKARA

TÜRK STANDARDI
TURKISH STANDARD

TS ISO 6474
Ocak 2005

1.Baskı

ICS 11.040.40

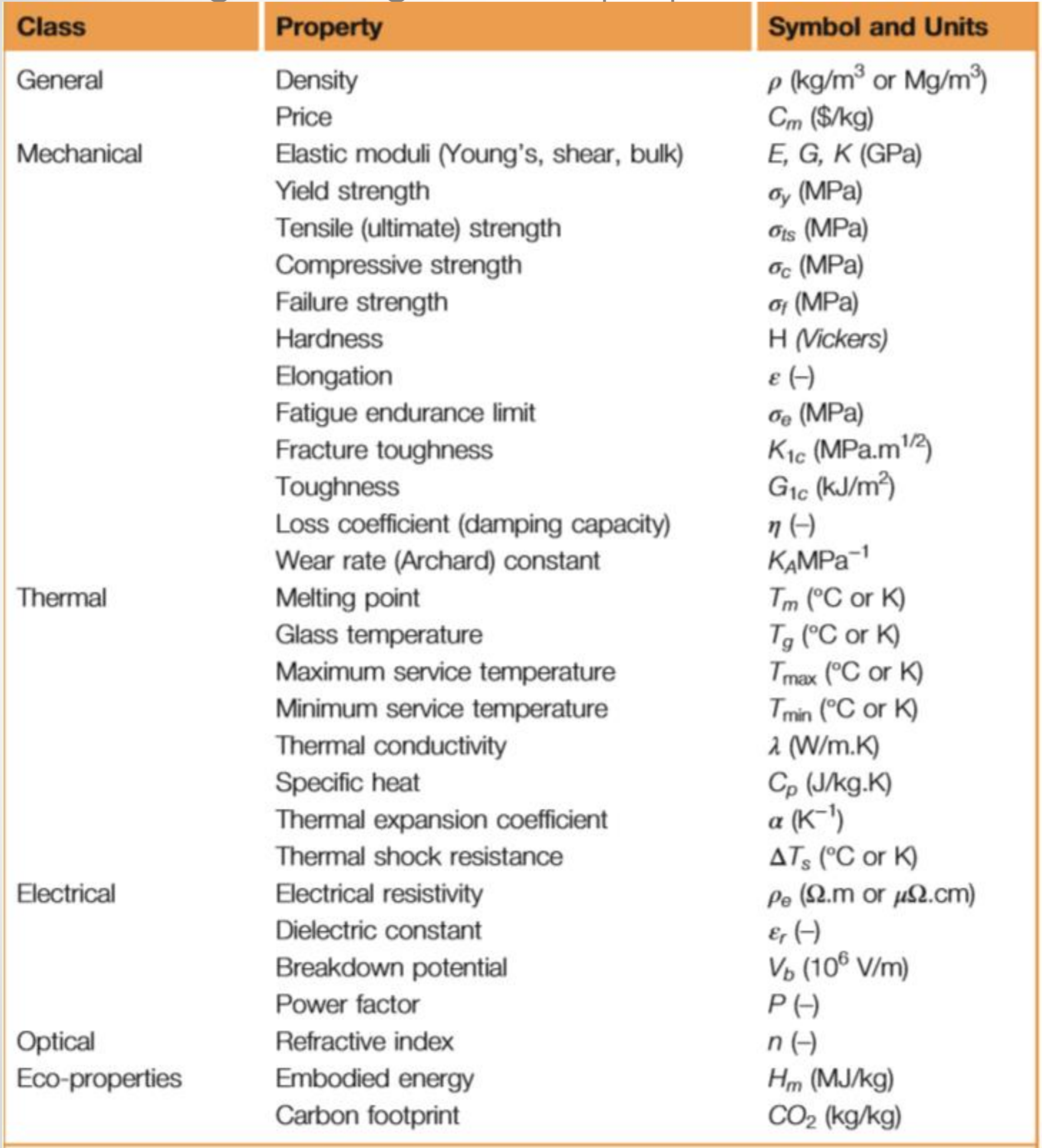
CERRAHİ İMPLANTLAR - SERAMİK MALZEMELER - YÜKSEK SAFLIKTA ALÜMİNA ESASLI

Implants for surgery; ceramic materials based on high purity alumina

TÜRK STANDARDLARI ENSTİTÜSÜ
Necatibey Caddesi No.112 Bakanlıklar/ANKARA

All the necessary information for a material to convert to a successful product is knowledge

Basic design limiting material properties and their SI units



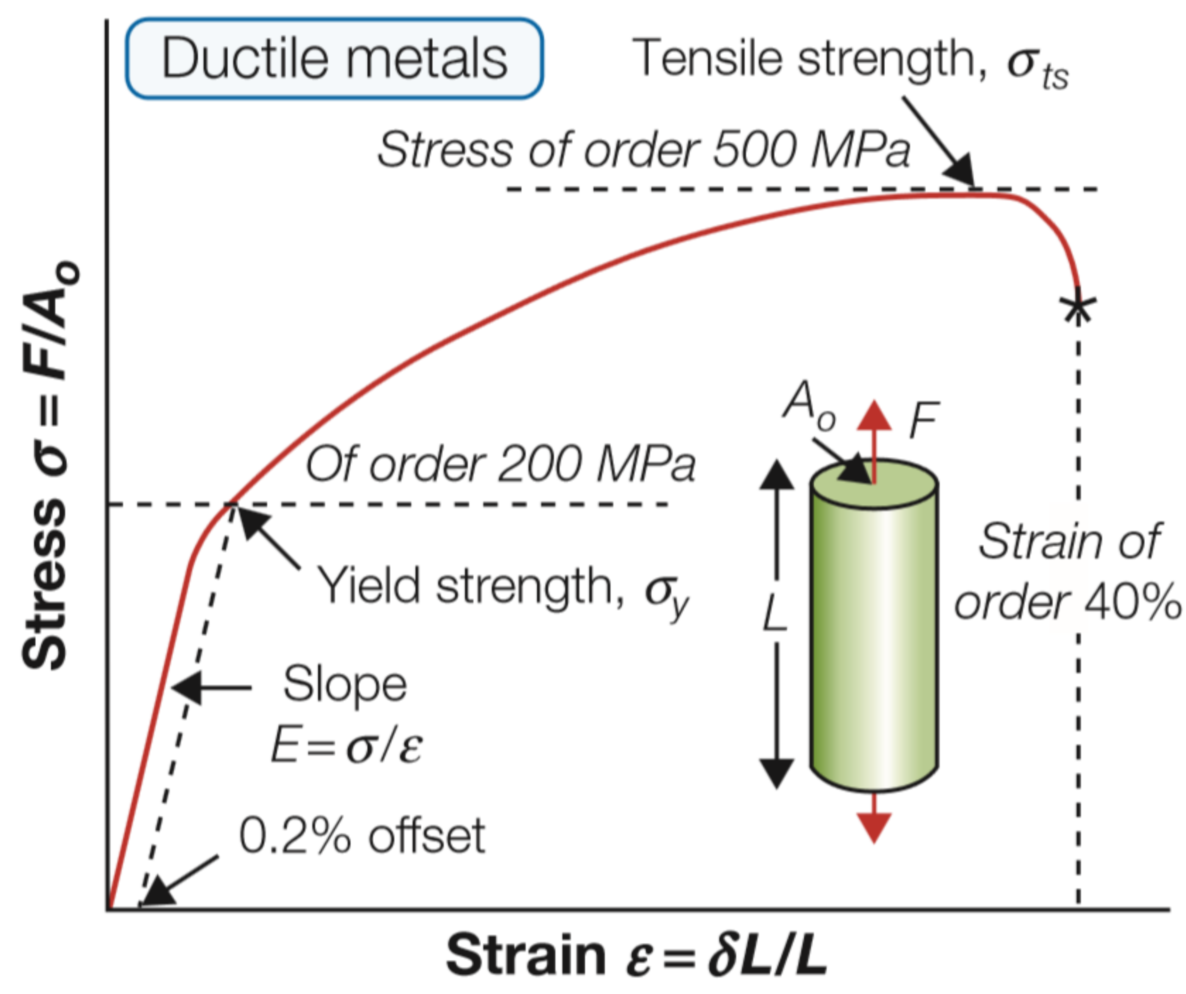
Class	Property	Symbol and Units
General	Density	ρ (kg/m^3 or Mg/m^3)
	Price	C_m (\$/kg)
Mechanical	Elastic moduli (Young's, shear, bulk)	E, G, K (GPa)
	Yield strength	σ_y (MPa)
	Tensile (ultimate) strength	σ_{ts} (MPa)
	Compressive strength	σ_c (MPa)
	Failure strength	σ_f (MPa)
	Hardness	H *(Vickers)*
	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)

Density is measured simply using Archimedes' method by weighing in air and in a fluid of known density

Price, \$/kg fluctuates depending on time, quantity you want and your status as a preferred customer with the vendor

An approximate price is used in the early stages of material selection

Mechanical properties

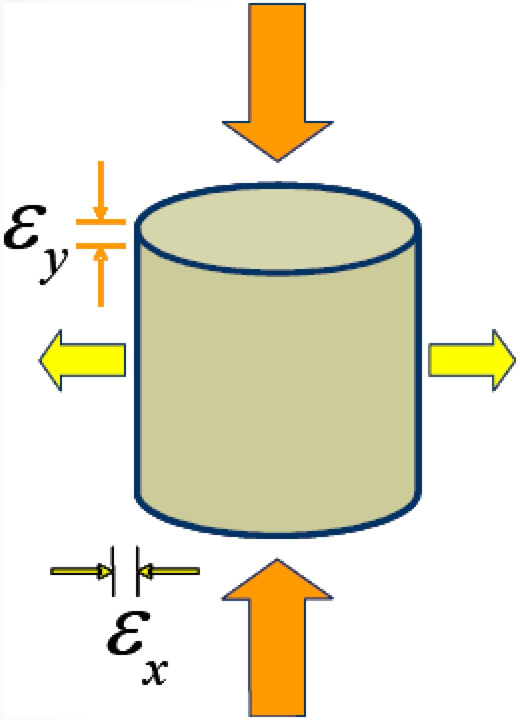


Elastic modulus, E is the slope of the initial linear-elastic part of the stress-strain curve

Moduli measured as slopes of stress-strain curves are inaccurate, about half the real value because of contributions to the strain from inelasticity, creep and other factors

Moduli are accurately measured dynamically by measuring the velocity of sound waves in the material

Mechanical properties



In an axial loading,

Poisson's ratio, v is the negative of the ratio of the lateral strain, ε_x to the axial strain, ε_y

$$\nu = -\frac{\varepsilon_x}{\varepsilon_y}$$

E describes response to tensile or compressive axial loading

G describes response to shear loading

K describes response to hydrostatic pressure

Moduli in an isotropic material are related in the following ways:

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

- Commonly, $v \approx 1/3$, $G \approx 3E/8$, $K \approx E$ But for elastomers,
- $v \approx 1/2$, $G \approx E/3$, $K >> E$

Strength of a solid requires careful definition

σ_f for metals is identified with the 0.2% offset yield strength σ_y and is the same in tension and compression

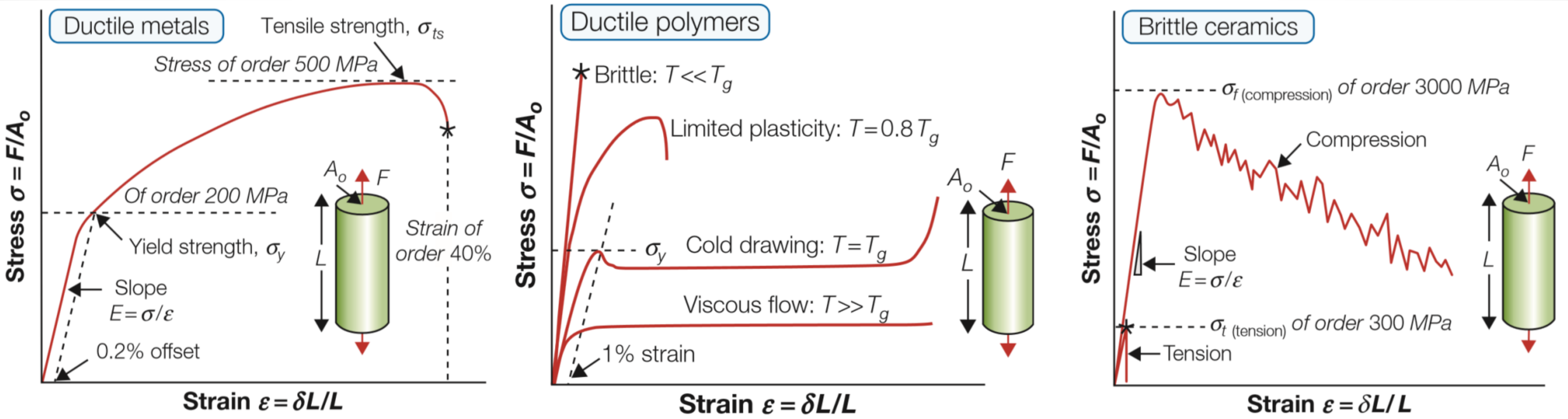
σ_f for polymers is identified as the stress at which the stress-strain curve becomes linear, at a strain typically of 1%

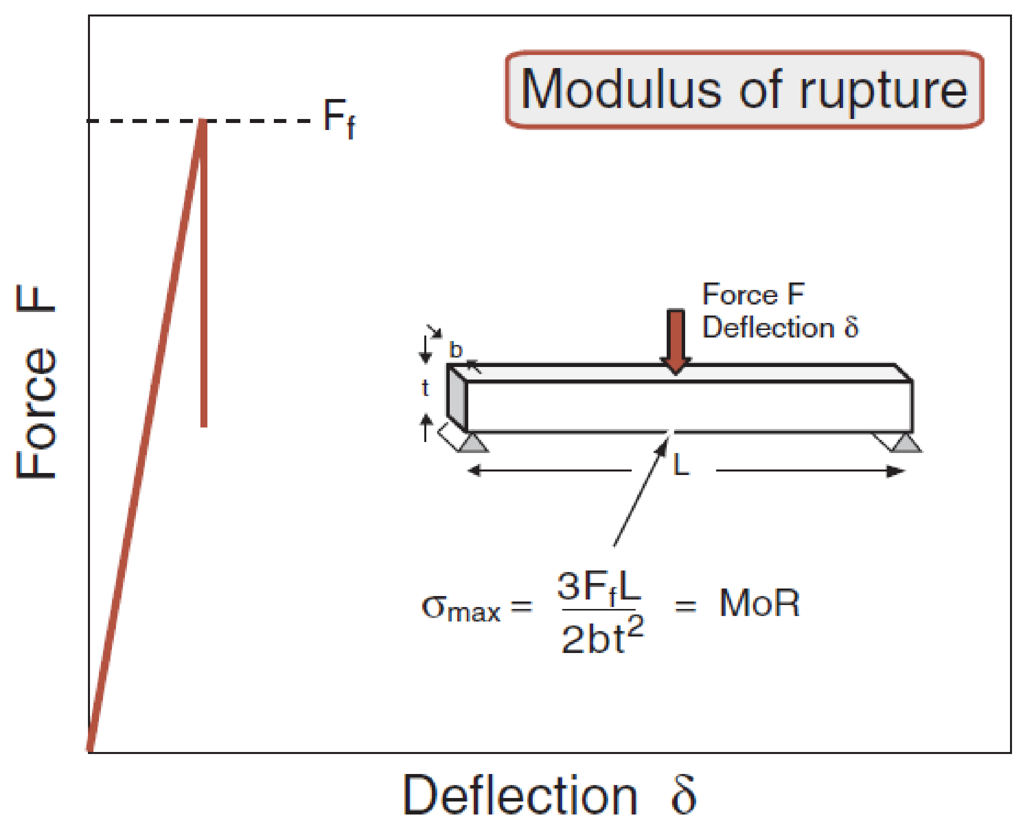
Polymers are stronger in compression (20%) than in tension

σ_f for ceramics and glasses depend on the mode of loading

In tension strength means the fracture strength, σ_t

In compression it means the crushing strength, σ_c Typically σ_c = 10-15 σ_t





When a material is difficult to grip, as is a ceramic, its strength can be measured in bending

The flexural strength or modulus of rupture, σ_{flex} is the maximum surface stress in a bent beam at the instant of failure

For ceramics, σ_{flex}=1.3 σ_t because the volume subjected to the maximum stress is small and the probability of a large flaw lying in it is correspondingly small

Strength of a composite is best defined by a deviation from linear-elastic behavior, an offset of 0.5% is taken

Composites that contain fibers, including natural composites such as wood are slightly weaker in compression (up to 30%) than in tension because fibers buckle

σ_f for composites is identified as the tensile strength σ_t

Hence strength depends on material class and on mode of loading

Other modes of loading are possible such as shear loading

Yield under multiaxial loads is related to that in simple tension by a yield function

For metals:

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2{\sigma_f}^2$$

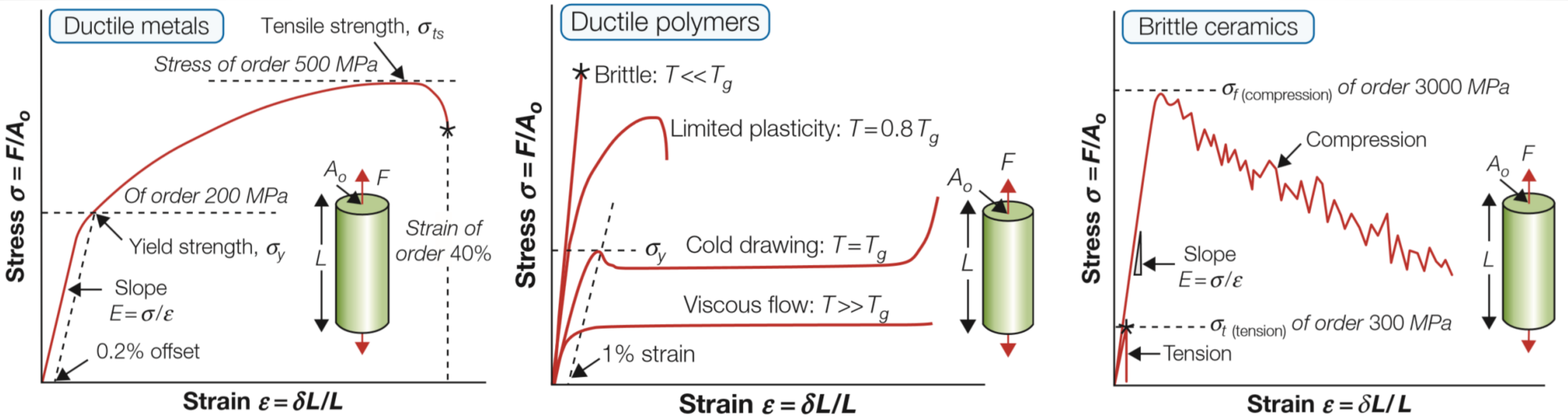
where σ_1, σ_2, σ_3 are the principal stresses, positive when tensile

σ_1 is the greatest, σ_3 the smallest

The tensile or ultimate strength σ_{ts} is the nominal stress at which a round bar of the material that is loaded in tension separates

For metals, ductile polymers and most composites, it is greater than the yield strength by a factor of 1.1 – 3 because of work hardening or load transfer to the reinforcement

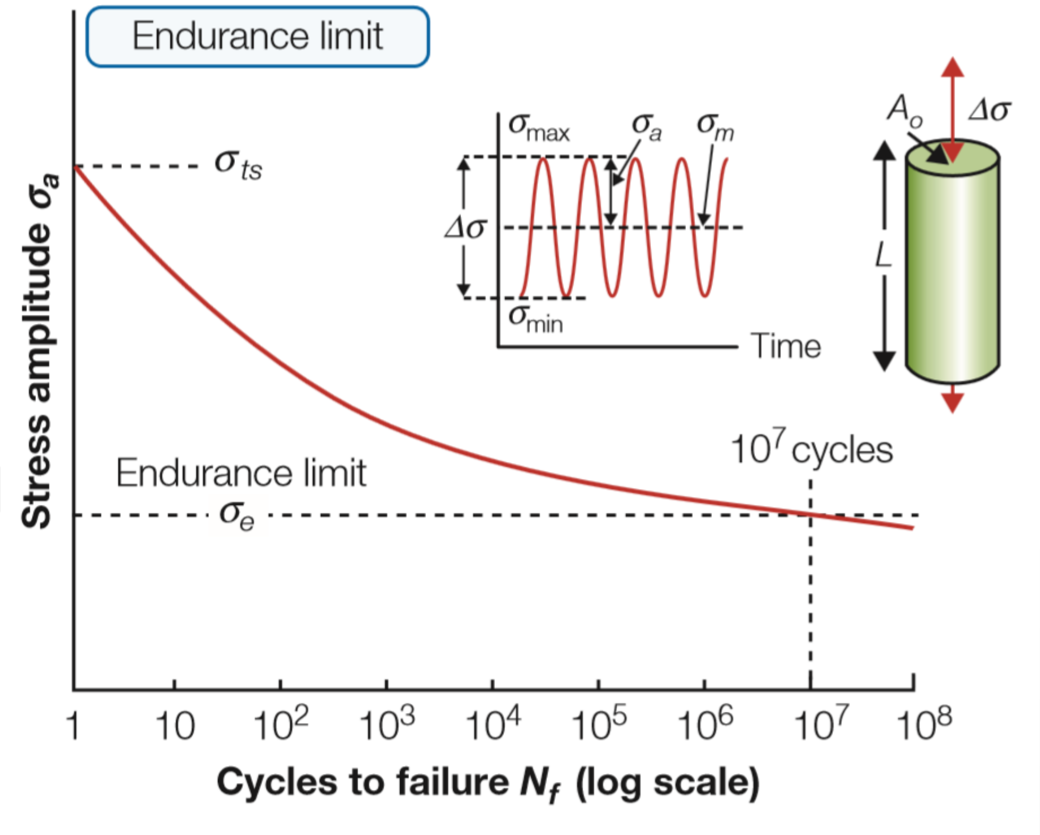
It is the same as the failure strength in tension for brittle solids like ceramics, glasses and brittle polymers



Cyclic loading can cause a crack to nucleate and grow in a material, resulting in fatigue failure

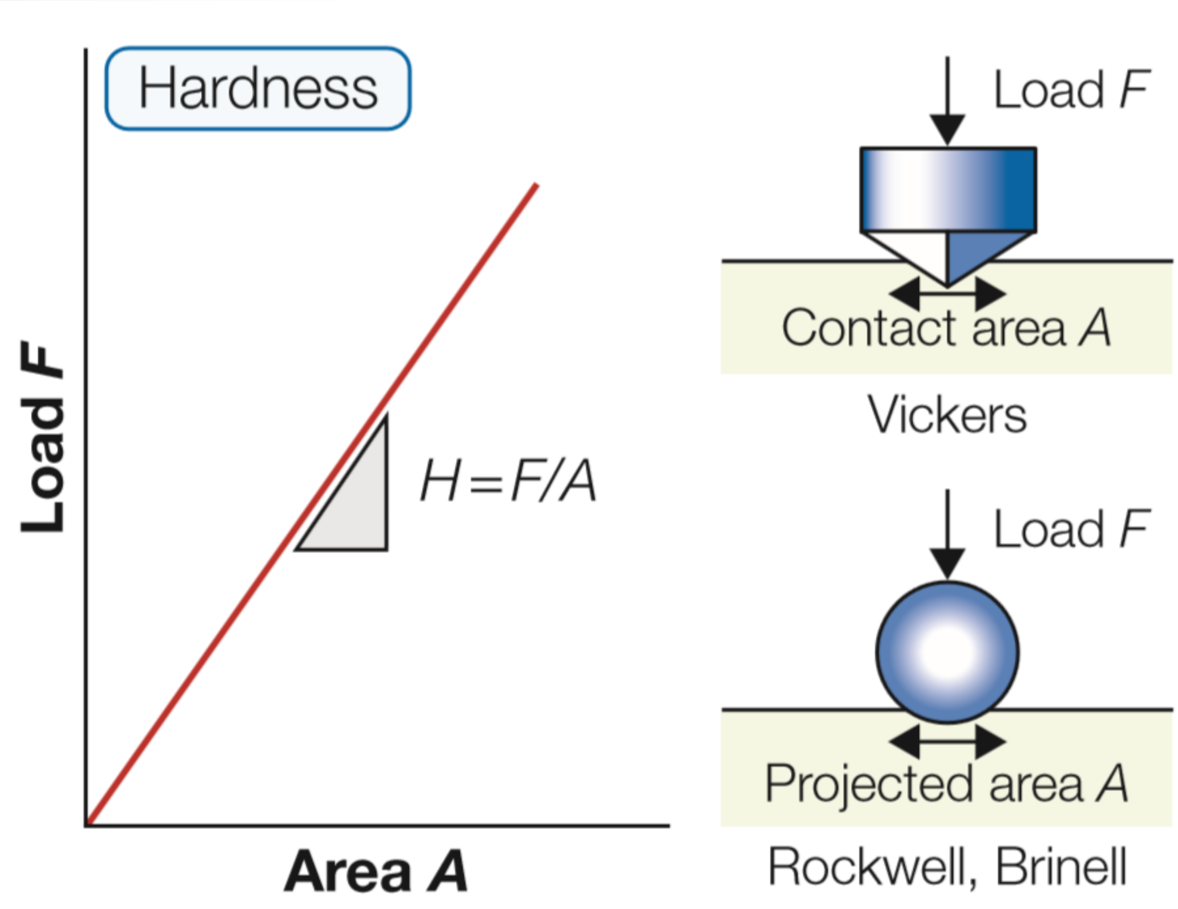
There exists a fatigue or endurance limit σ_e for many materials

It is the stress amplitude $\Delta\sigma$ below which fracture does not occur or occurs after a very large number of cycles



Hardness

The hardness test gives an approximate, nondestructive measure of the strength while tensile and compression tests need a large sample and destroy it



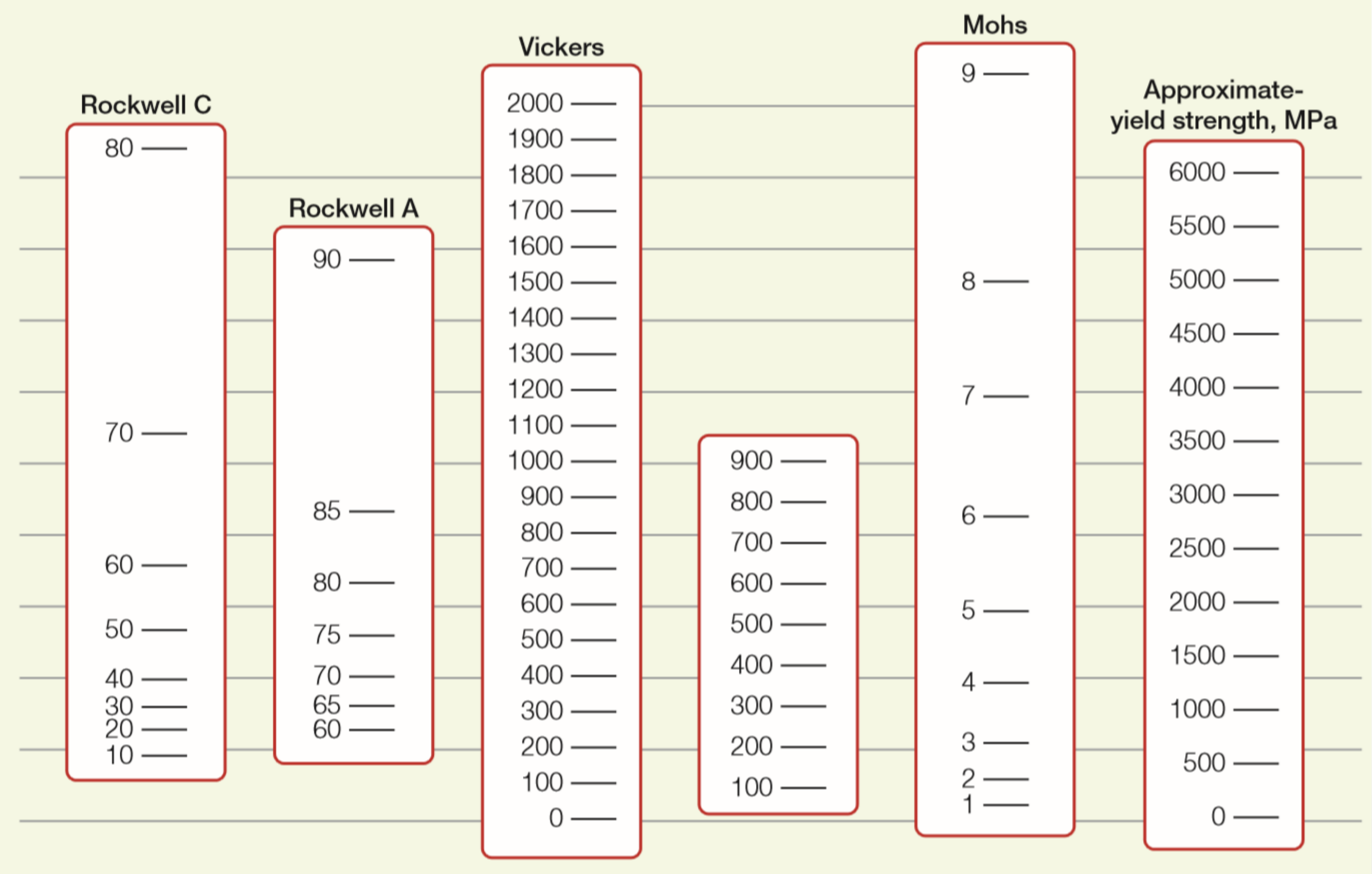
Hardness, H of a material is measured by pressing a pointed diamond or hardened steel ball into the material's surface

Hardness is defined as the indenter force divided by the projected area of the indent

Hardness is commonly reported in a wide range of units other than MPa

The most common is the Vickers, H_v scale with units of kg/mm^2

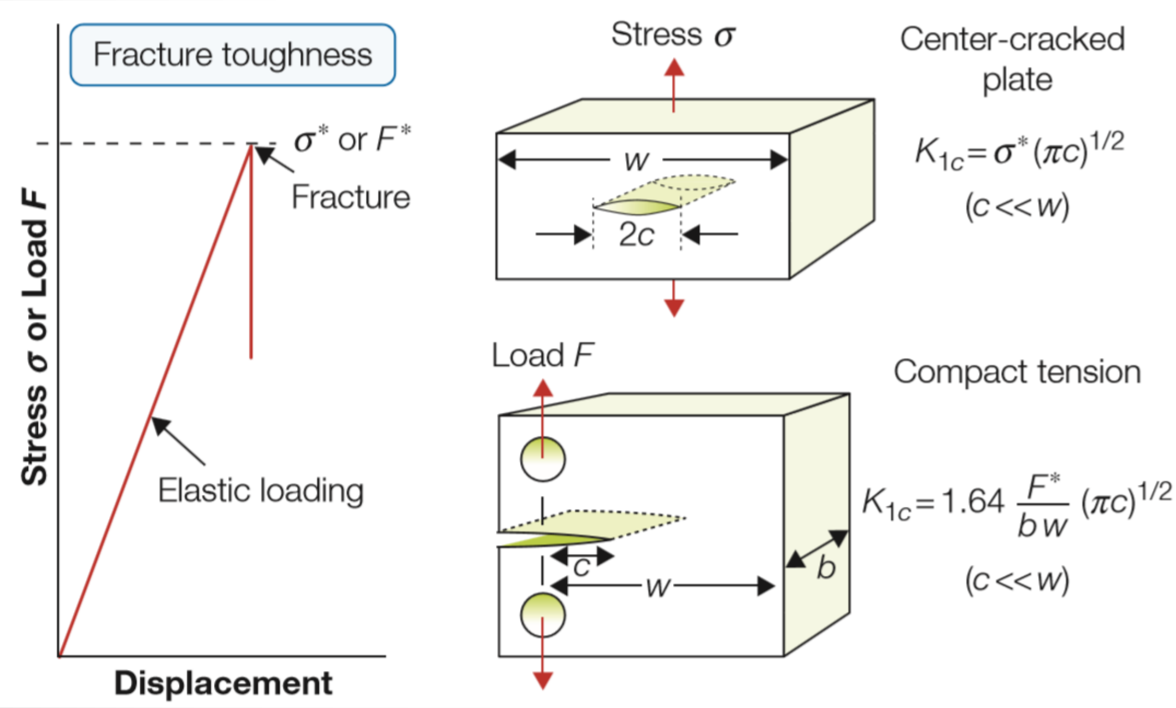
$$H \approx 3\sigma_f, \; H_v = H/10$$



Toughness, G_{1c} (kJ/m^2) and the fracture toughness, K_{1c} (MPa/m$^{1/2}$) measure the resistance of a material to the propagation of a crack

Fracture toughness is measured by loading a sample containing a deliberately introduced crack of length 2c, recording the tensile strength σ^* at which the crack propagates

$$K_{1c} = Y\sigma^*\sqrt{\pi c}$$



$$G_{1c} = \frac{{K_{1c}}^2}{E(1+\nu)}$$

Where Y is a geometric facto near unity that depends on details of the sample geometry, E is Young's modulus and ν is Poisson's ratio

The loss coefficient, *η* is a dimensional quantity that measures the degree to which a material dissipated vibrational energy

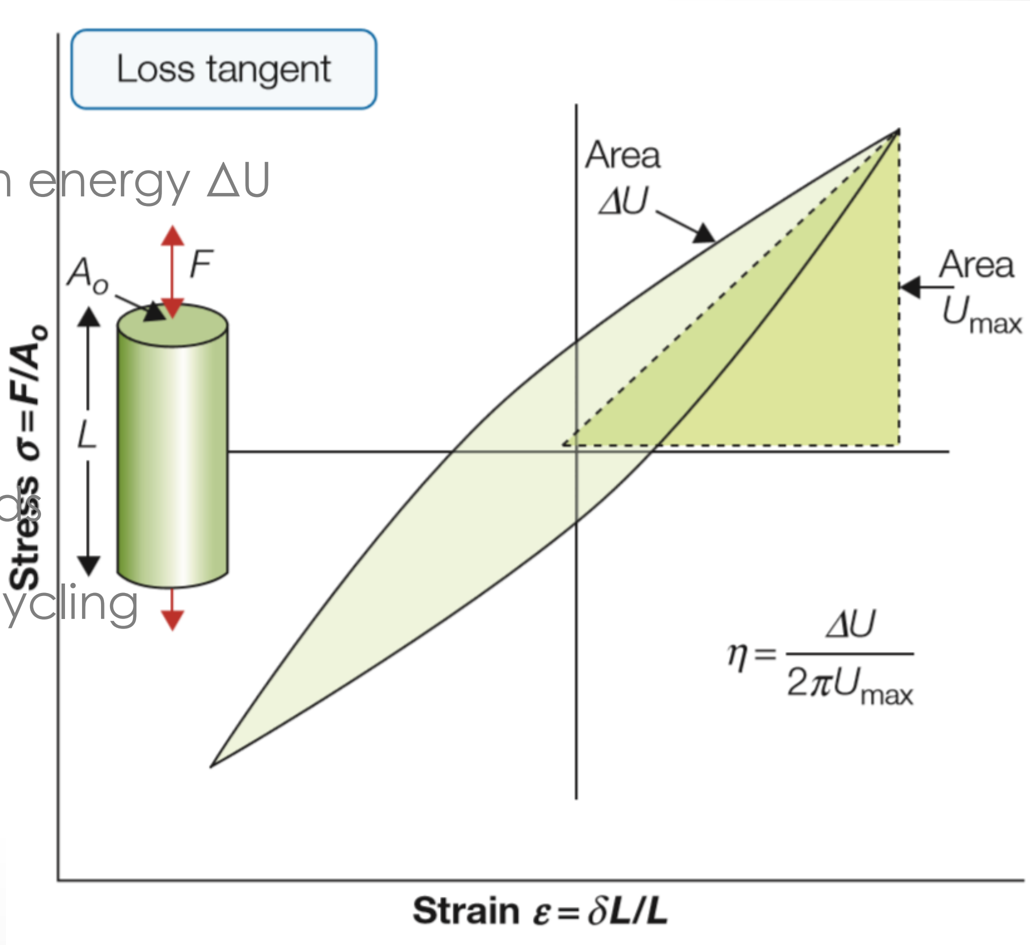
If a material is loaded elastically to a stress σ_{max}, it stores an elastic energy U per unit volume

$$U = \oint_0^{\sigma_{max}} \sigma d\varepsilon \approx \frac{1}{2}\frac{\sigma_{max}{}^2}{E}$$

If it is then unloaded, it dissipates an energy ΔU

$$\Delta U = \oint \sigma d\varepsilon$$

The value of loss coefficient depends on the time scale or frequency of cycling



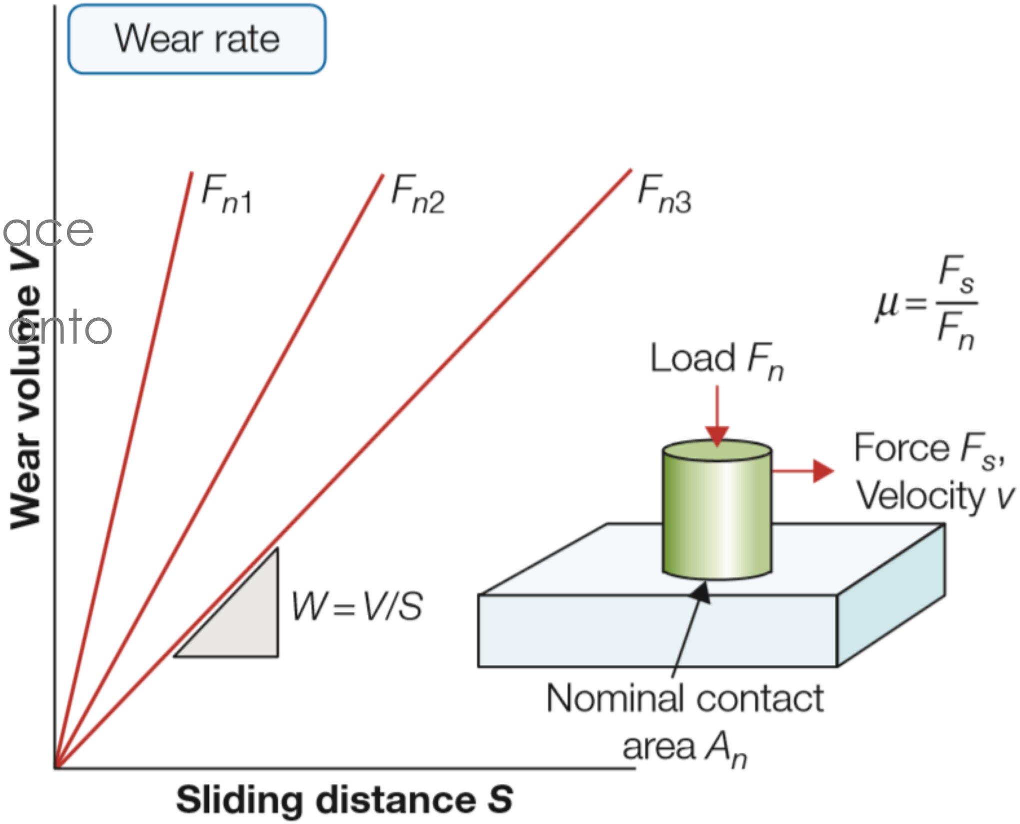
The loss of a material when surfaces slide against each other or Wear, is a multibody problem

When solids slide, the volume of material lost from one surface, per unit distance slid, is called the wear rate, W (m^2)

The wear resistance of a surface is characterized by the Archard wear constant, K_A (1/MPa)

$$\frac{W}{A} = K_A P$$

Where A is the area of the slider surface and P is the normal force pressing it onto the other surface



Thermal properties

Two temperatures, the melting temperature T_m, and the glass transition temperature T_g, are fundamental because they relate directly to the strength of the bonds in the solid

Crystalline solids have a sharp melting point, T_m

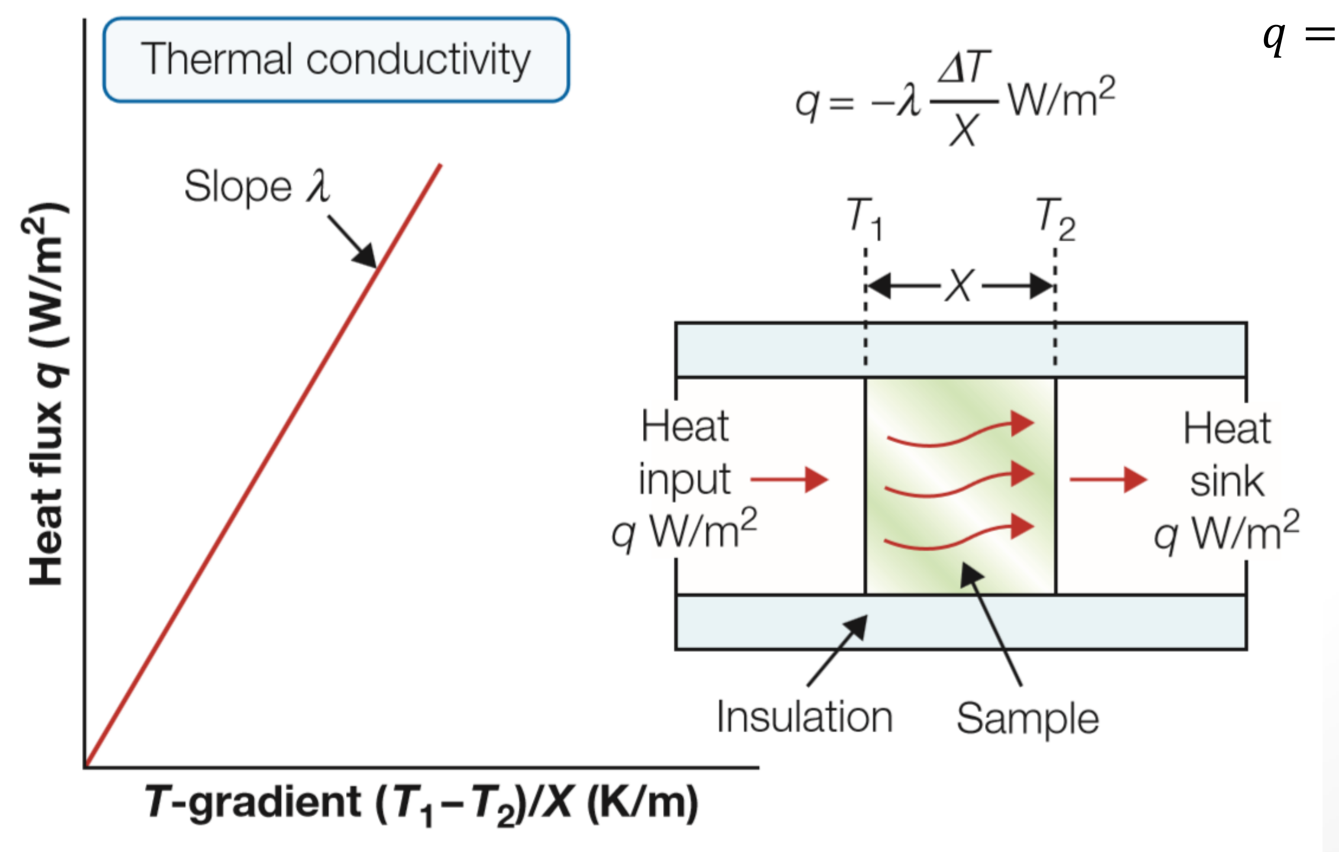
Noncrystalline solids do not, the glass transition temperature T_g characterizes the transition from true solid to very viscous liquid

The maximum service temperature T_{max} is the highest temperature at which the material can reasonably be used without oxidation, chemical change or creep

The minimum service temperature T_{min} is the temperature below which the material becomes brittle or otherwise unsafe to use

The rate at which heat is conducted through a solid at steady state is measured by the thermal conductivity, λ (W/mK)

It is measured by recording the heat flux q flowing through the material from a surface at higher temperature T_1 to a lower one at temperature T_2 separated by a distance X

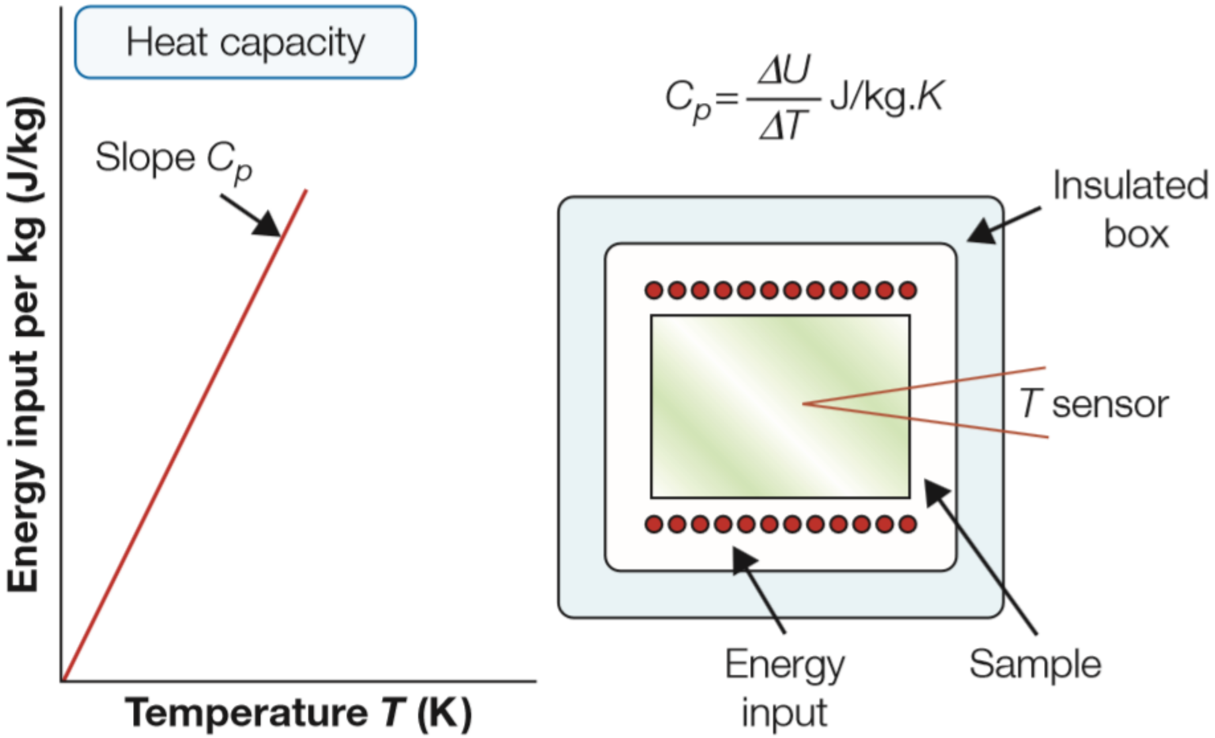


$$q = -\lambda \frac{dT}{dX} = \lambda \frac{(T_1 - T_2)}{X}$$

The heat capacity or specific heat C (J/kgK) is the energy to heat 1 kg of a material by 1 K

The heat capacity is measured by calorimetry which is also the standard way of measuring the glass transition temperature

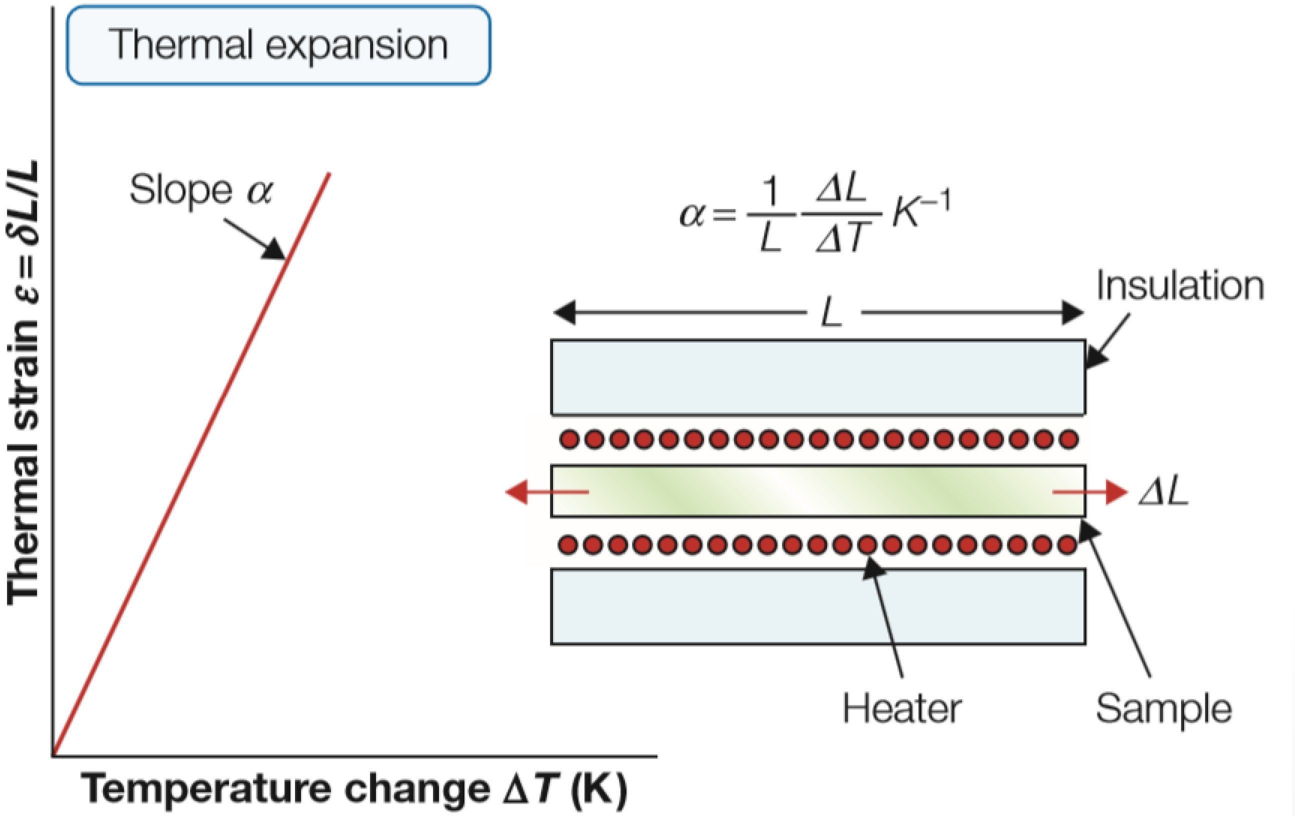
A measured quantity of energy is pumped into a sample of a material of known mass while the temperature rise is measured



Most materials expand when they are heated

The thermal strain per degree of temperature schange is measured by the linear thermal expansion coefficient, a (1/K)

The thermal shock resistance, ΔT (K) is the maximum temperature difference through which a material can be quenched without damage



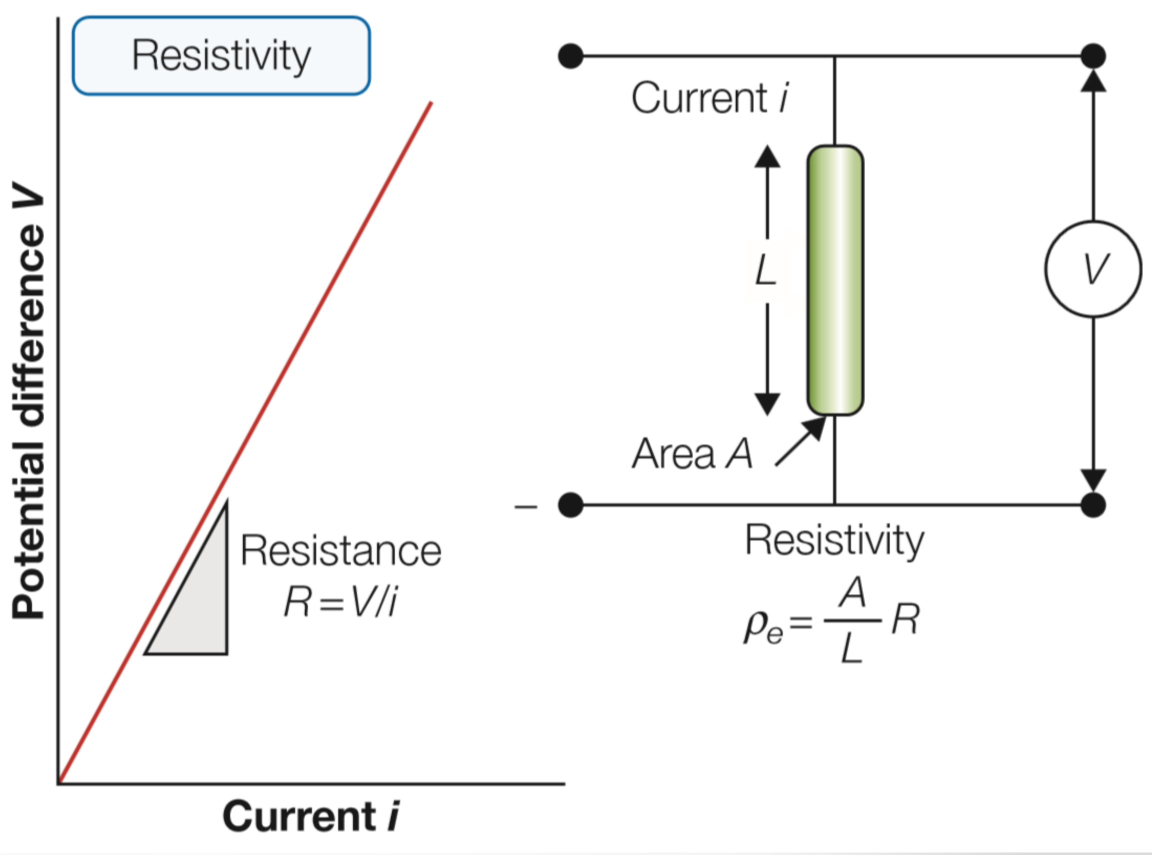
The electrical resistivity, ρ_e (Ωm) is the resistance of a unit cube with unit potential difference between a pair of its faces

It ranges from 10^{-8} for good conductors to more than 10^{16} for the best insulators

The electrical conductivity, κ_e (Siemens/m) is the reciprocal of the resistivity

When an insulator is placed in an electric field, it becomes polarized and charges appear on its surface that tend to screen the interior from the electric field

Dielectric constant, ε_γ measures the tendency of an insulating material to polarize



All materials allow for some passage of light, although it is exceedingly small for metals

The speed of light v in the material is always less than that c in vacuum

A consequence of that is a beam of light striking the surface of such a material at an angle of incidence α, enters the material at an angle β, the angle of refraction

The refractive index, n is

$$n = \frac{c}{v} = \frac{\sin \alpha}{\sin \beta}$$

It is related to the dielectric constant at the same frequency by

$$n \approx \sqrt{\varepsilon_\gamma}$$

The refractive index depends on wavelength and thus on the color of the light

The denser the material, and the higher its dielectric constant, the greater the refractive index

Eco properties

The embodied energy (MJ/kg) is the energy required to extract 1 kg of a material from its ores or feedstock

The associated CO_2 footprint (kg/kg) is the mass of carbon diaoxide released into the atmosphere during the production of 1 kg of material

Materials Selection Diagrams

Material attributes determine the performance of the design

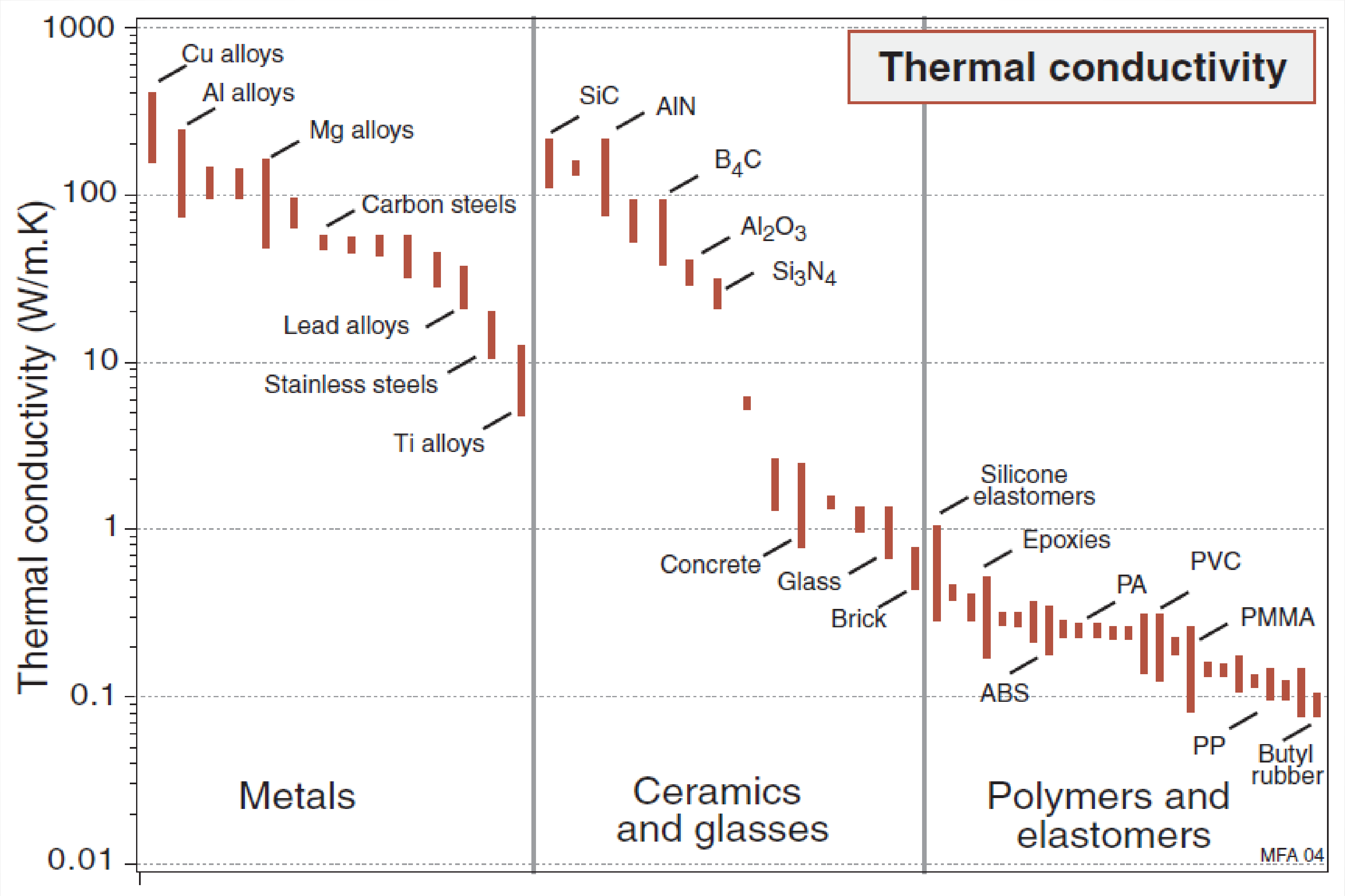
An efficient way of relating material attributes and property requirements dictated by the design is the analysis of material selection diagrams

A property can be described simply by a bar graph

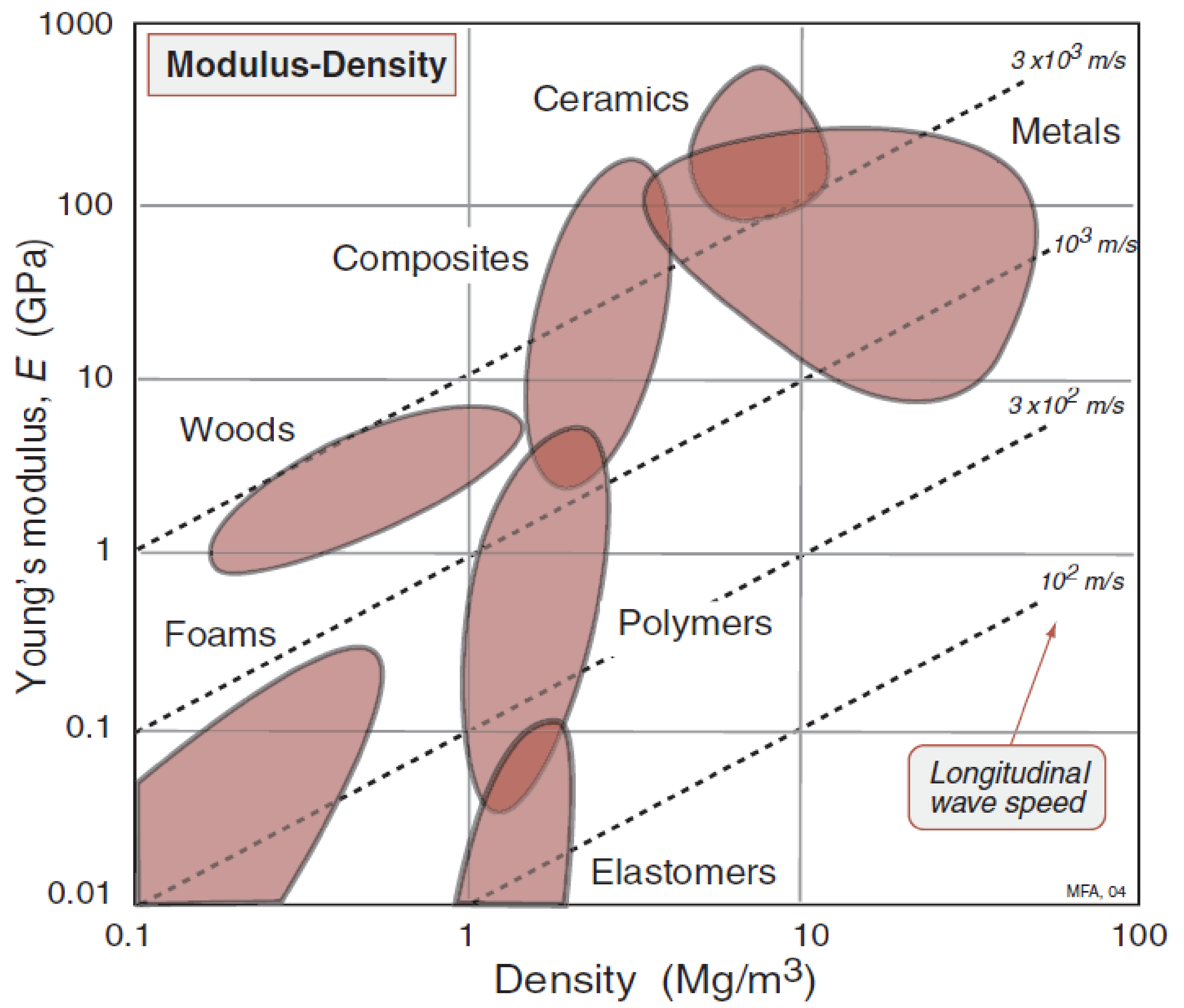
However a design constraint is seldom a function of one property

Most design constraints are represented as a combination of material attributes

For example, strength/density ratio (σ_f/ρ) or modulus/density ratio (E/ρ) are aimed to be maximized for light weight mechanical design



Most attributes of engineering materials vary in a wide range and bar graphs are convinient ways to demonstrate them



Plotting one property as a function of another is the convenient way to demonstrate a wealth of information

The velocity of sound waves traveling in a material depends on the modulus and density

This enables the engineer relate the two axes E and ρ on the diagram

$$v = \left(\frac{E}{\rho}\right)^{1/2} \Longrightarrow \log E = \log \rho + 2 \log v$$

The equation forms a straight line for a constant sound wave

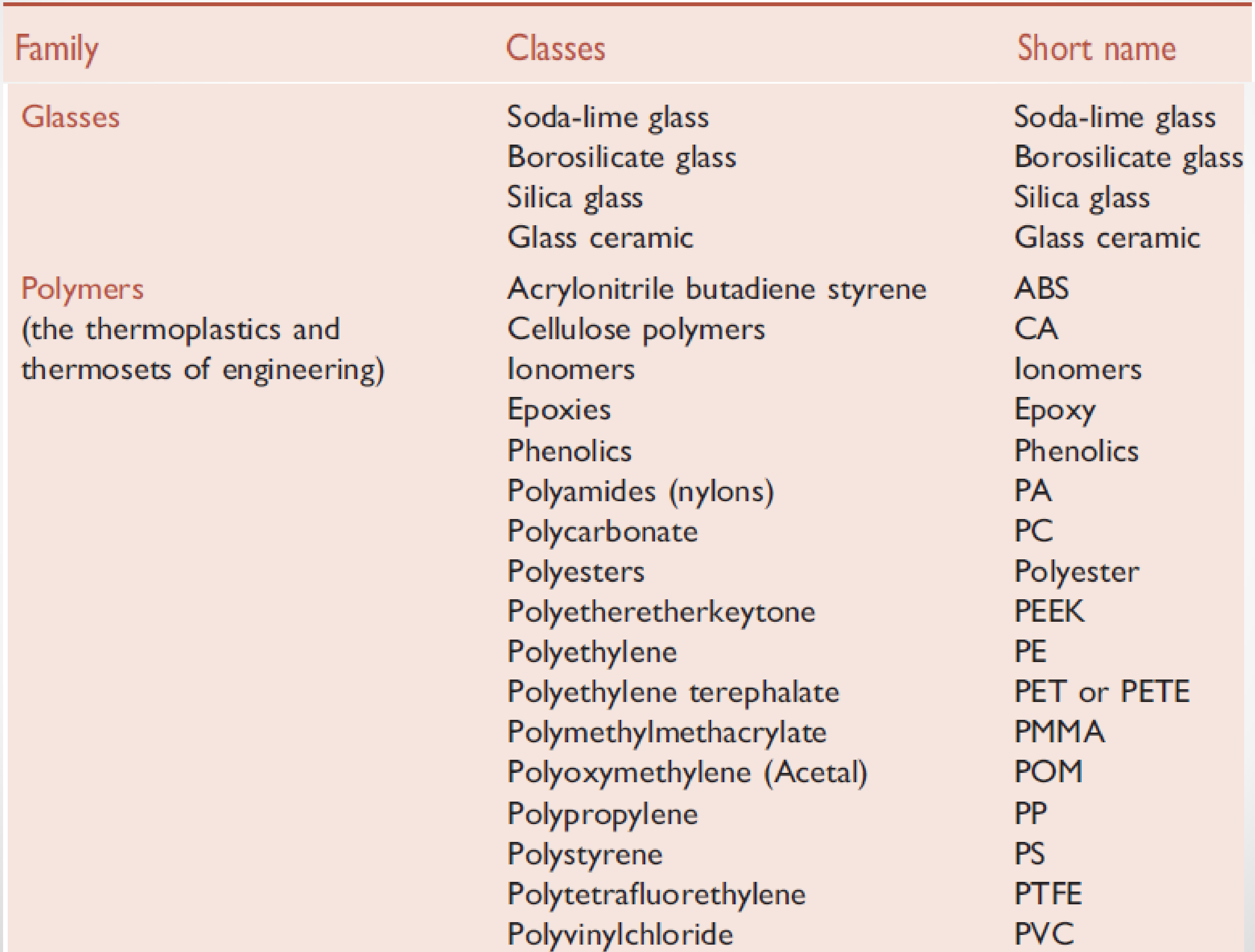
Contours of constant wave velocity are material indices

A material index is a parameter combining the significant properties of the design

Material Families and Classes

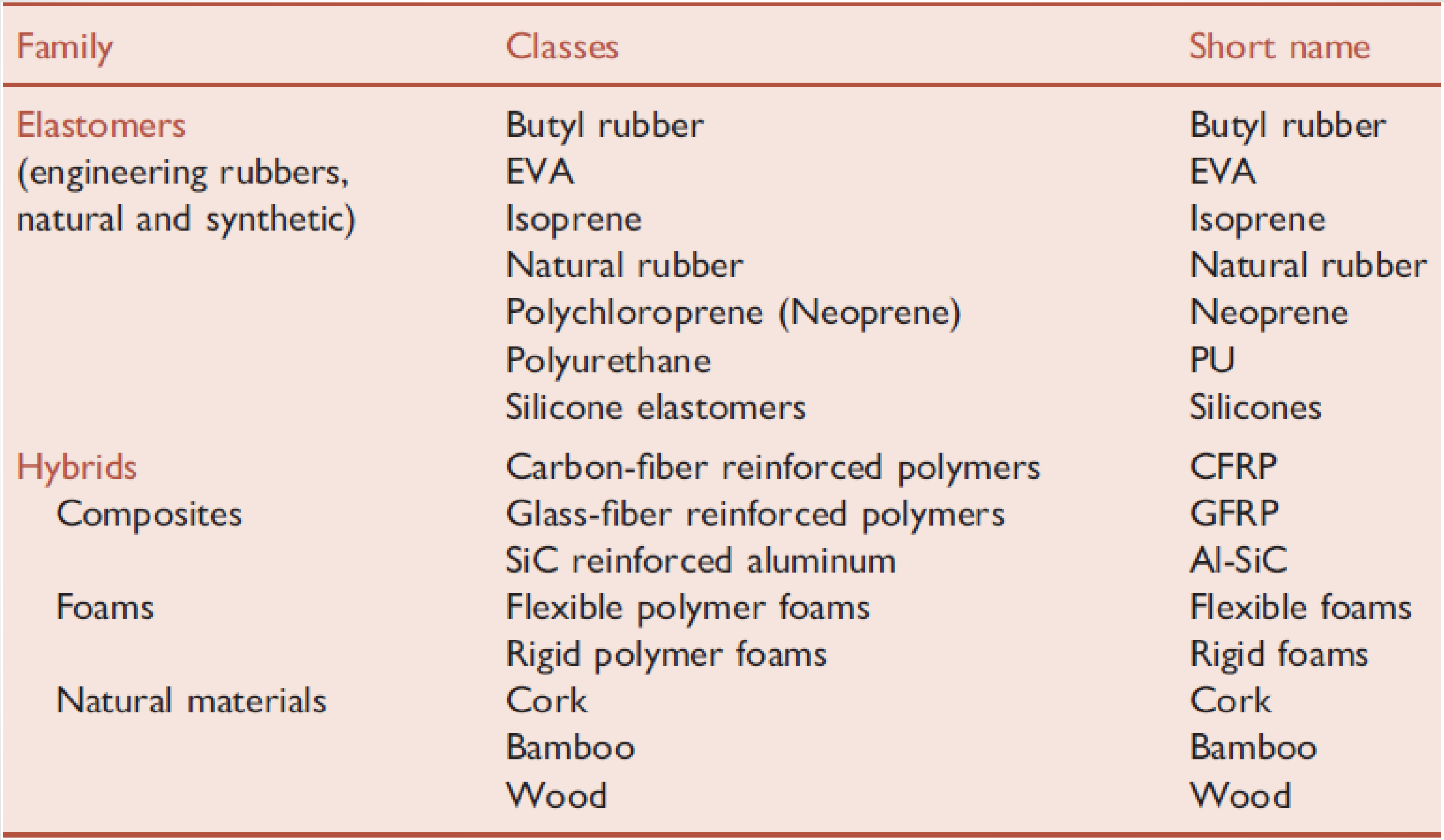
Family	Classes	Short name
Metals (the metals and alloys of engineering)	Aluminum alloys	Al alloys
	Copper alloys	Cu alloys
	Lead alloys	Lead alloys
	Magnesium alloys	Mg alloys
	Nickel alloys	Ni alloys
	Carbon steels	Steels
	Stainless steels	Stainless steels
	Tin alloys	Tin alloys
	Titanium alloys	Ti 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
Non-technical ceramics (porous ceramics of construction)	Brick	Brick
	Concrete	Concrete
	Stone	Stone

Material Families and Classes



Family	Classes	Short name
Glasses	Soda-lime glass	Soda-lime glass
	Borosilicate glass	Borosilicate glass
	Silica glass	Silica glass
	Glass ceramic	Glass ceramic
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 terephalate	PET or PETE
	Polymethylmethacrylate	PMMA
	Polyoxymethylene (Acetal)	POM
	Polypropylene	PP
	Polystyrene	PS
	Polytetrafluorethylene	PTFE
	Polyvinylchloride	PVC

Material Families and Classes



Family	Classes	Short name
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	Carbon-fiber reinforced polymers	CFRP
Composites	Glass-fiber reinforced polymers	GFRP
	SiC reinforced aluminum	Al-SiC
Foams	Flexible polymer foams	Flexible foams
	Rigid polymer foams	Rigid foams
Natural materials	Cork	Cork
	Bamboo	Bamboo
	Wood	Wood

Material selection charts display data for about 30 properties for the families and classes of materials listed

The list is expanded from the original six families by distinguishing composites from foams and from natural materials, and by distinguishing the high-strength technical ceramics from the low-strength, non-technical ceramics

Within each family data are plotted for a representative set of materials that span the full range of behavior for the class and include the most common and most widely used members

Diagrams show a range of values of each property of each material as bubbles within the family envelope

Modulus vs Density Diagram

The density of a solid depends on the atomic weight of its atoms or ions, their size and the way they are packed

Size and packing of atoms do not affect density much

The spread of density comes mainly from the spread of atomic weight, ranging from 1 for H_2 to 238 for U

The moduli of most materials depend on 2 factors:

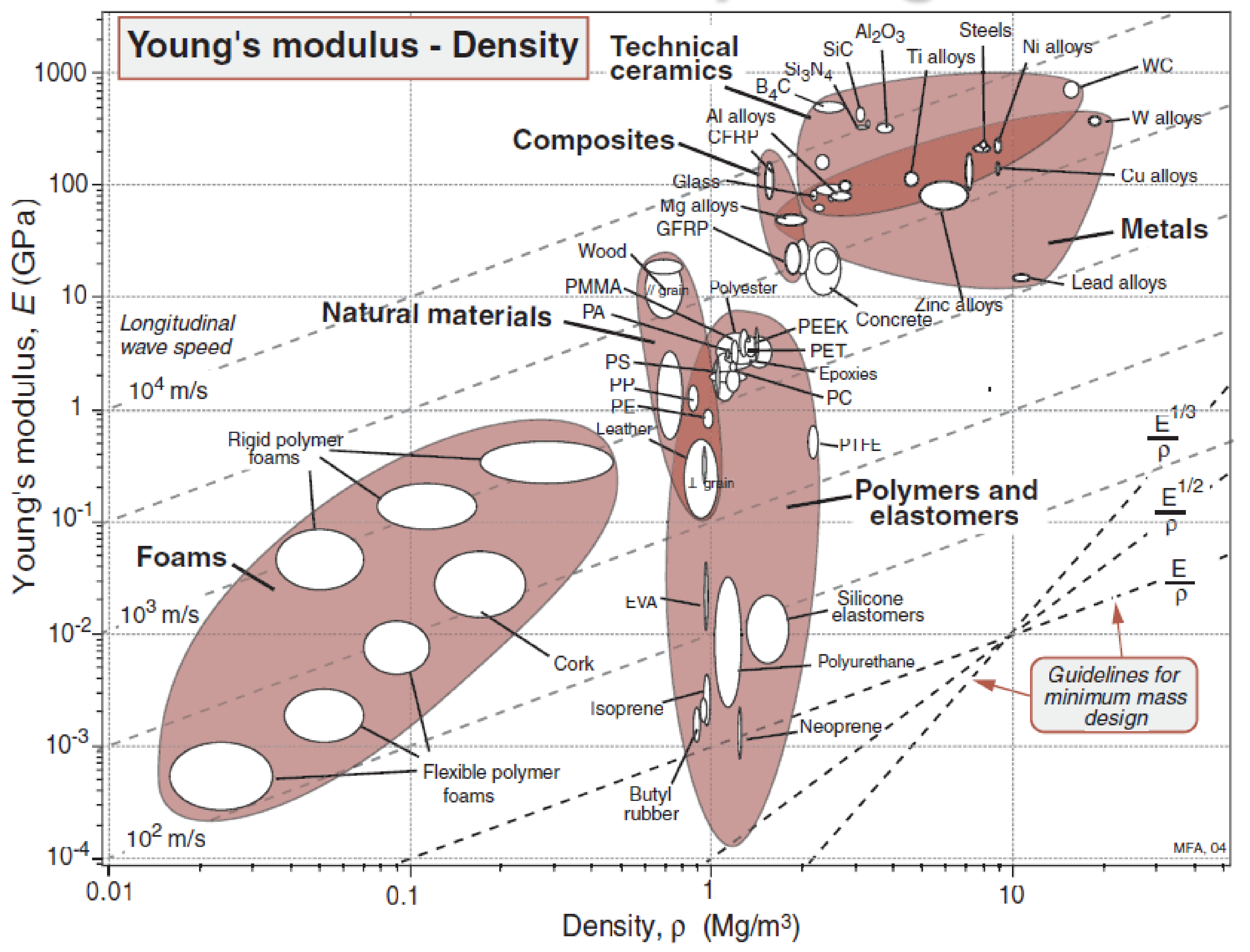
Bond stiffness (20-200 N/m for covalent, 10-100 for metallic and ionic, 0.5-2 for van der Waals and hydrogen bonds)

The lower limit for true solids

$$E = \frac{0.5}{3 \times 10^{-10}} \approx 1\,\mathrm{Gpa}$$

Elastomers and foams have moduli lower than 1 GPa

Modulus vs Density Diagram



Strength vs Density Diagram

The definition of strength is different for each material family due to different failure mechanisms

Strength of materials differ widely because of their different lattice resistances

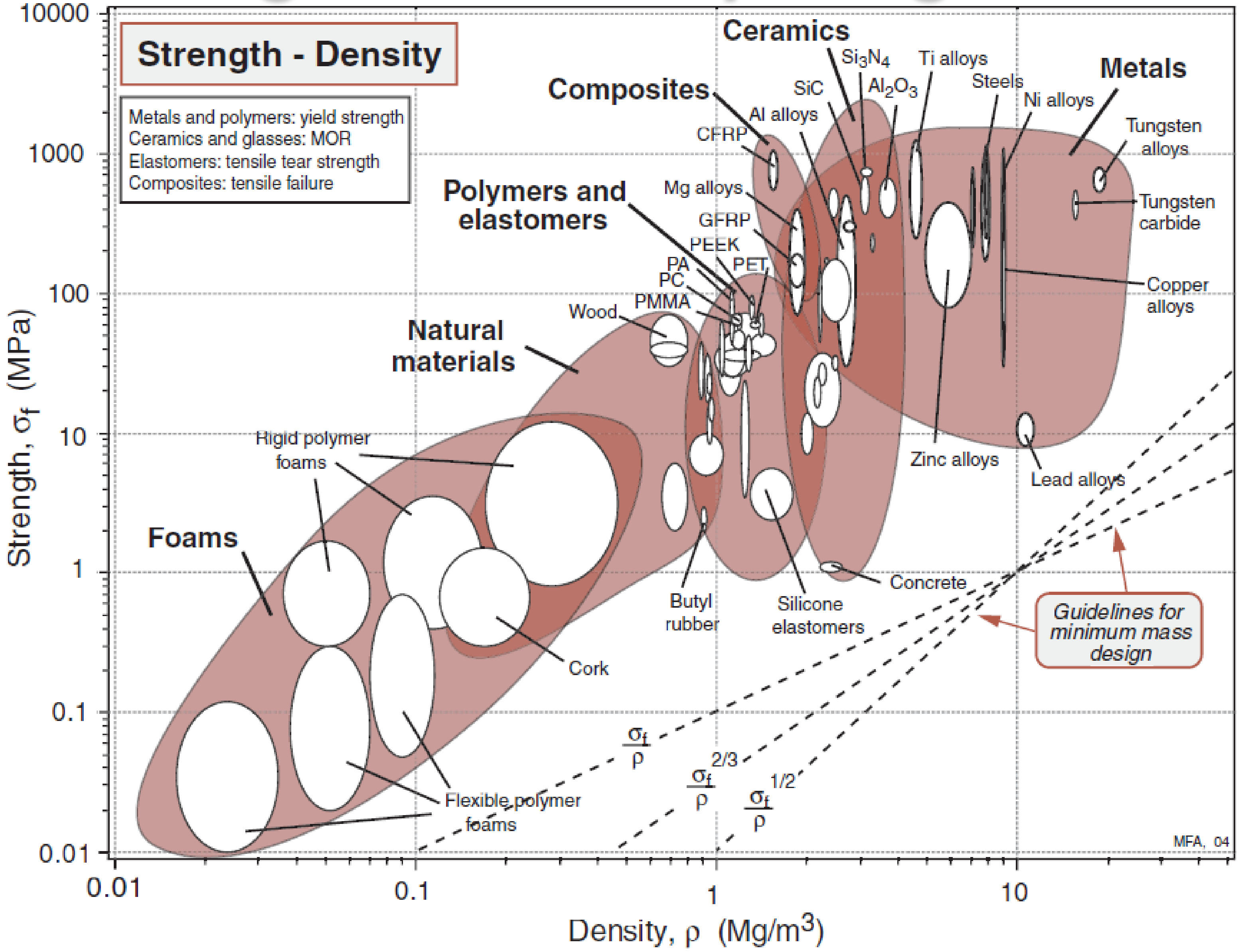
If a unit dislocation step involves breaking strong bonds like covalent, the material is strong

If it only involves the rupture of weak bonds like van der Waals, the material is weak

Materials that fail by fracture have very large lattice resistances so that atomic separation happens first

An important use of the diagram is in materials selection for lightweight structural design

Strength vs Density Diagram



Modulus vs Strength Diagram

Springs can be made of both high tensile strength steel and rubber

The useful comparison of strength to elastic modulus gives the yield strain

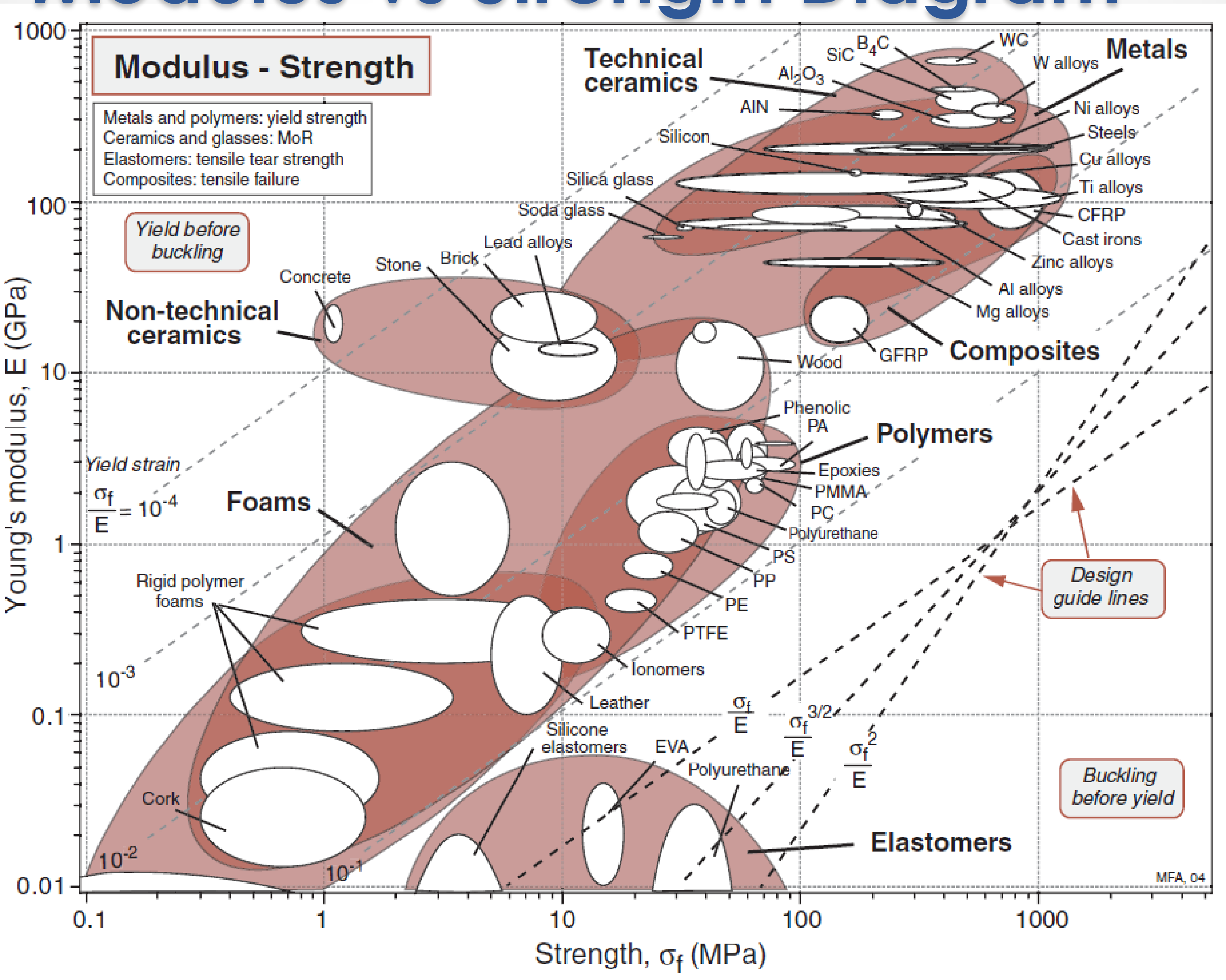
$$\frac{\sigma_f}{E} = \varepsilon$$

Yield strain is the strain at which the material ceases to be linearly elastic

Metals and ceramics that have the highest strengths of all materials have relatively low yield strain

Composites are close to metals, polymers about 10 times higher and elastomers have values of $\frac{\sigma_f}{E}$ larger than any other material family due to their low moduli

Modulus vs Strength Diagram



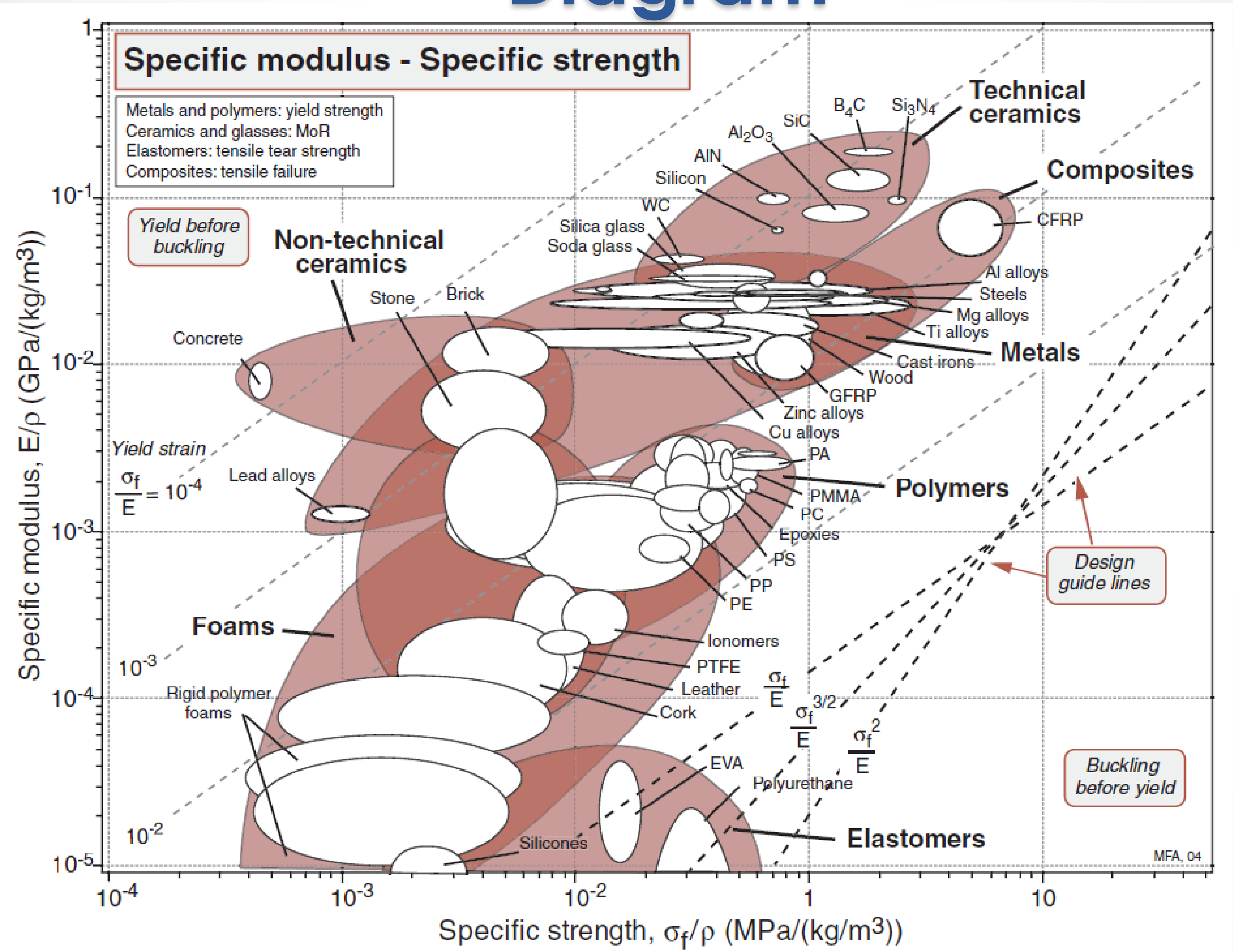
Specific Modulus vs Specific Strength Diagram

Many designs that are for moving parts require stiffness and strength at minimum weight

The data of the previous diagram is replotted after dividing each material by the density

Specific properties are measures of mechanical efficiency for the use of the least mass of material to do the most structural work

Specific Modulus vs Specific Strength Diagram



Fracture Toughness vs Modulus Diagram

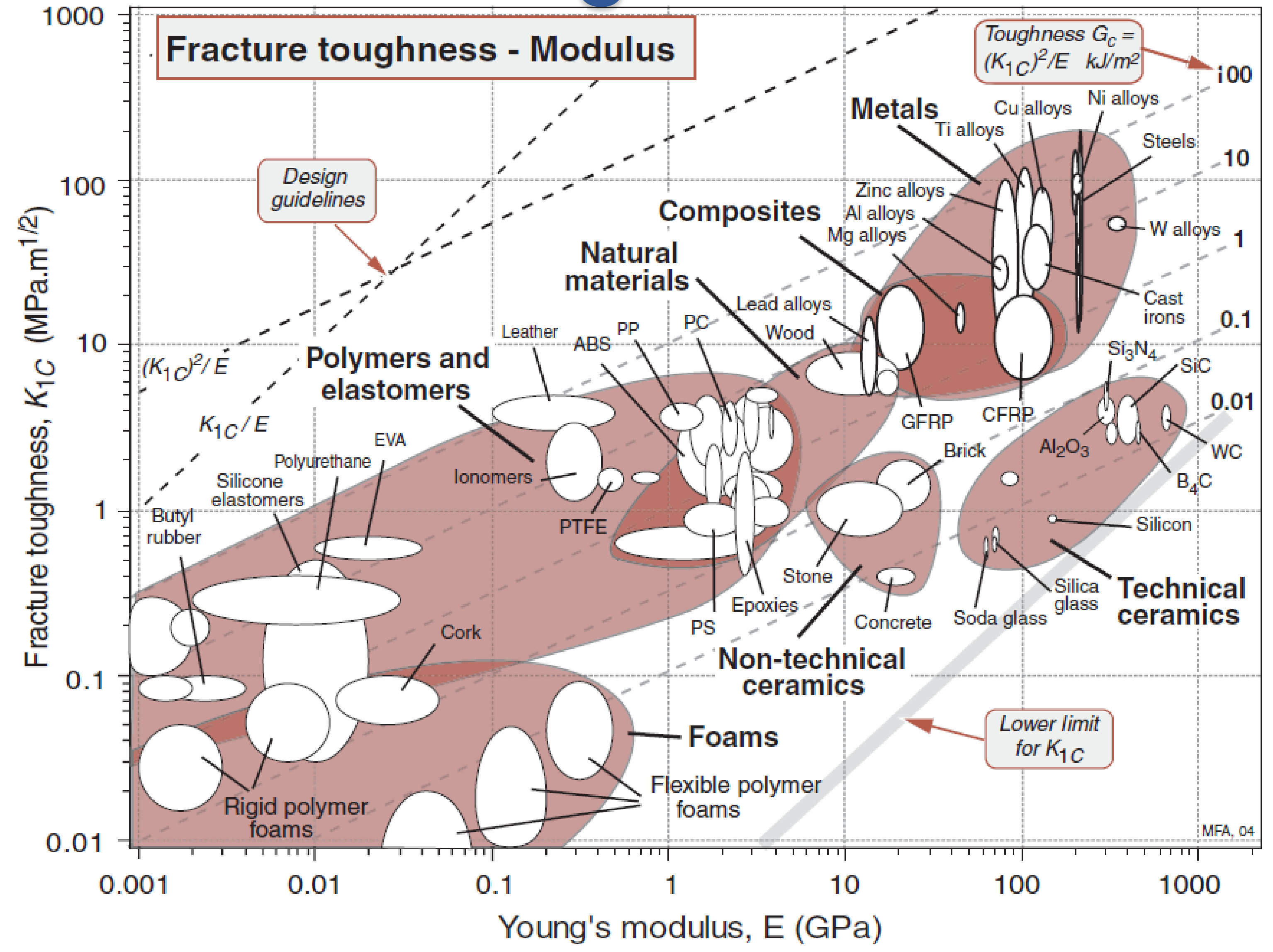
Increasing the strength of a material is useful only as long as the material remains plastic and does not become brittle

Fracture toughness of polymers is about the same as ceramics, however they are widely used in engineering structures while ceramics are used with caution

The necessary condition for fracture of the component is that sufficient elastic energy released to supply the surface energy of the two surfaces that are created

The energy absorbed by fracturing ceramics is only slightly more than the surface energy
When metals, polymers and composites fracture, the absorbed energy is much greater because of plasticity associated with crack propagation

Fracture Toughness vs Modulus Diagram



Fracture Toughness vs Strength Diagram

The stress concentrations at the tip of a crack generates a process zone; a plastic zone in ductile solids, micro-cracking zone in ceramics, delamination, debonding and fiber pull-out zone in composites

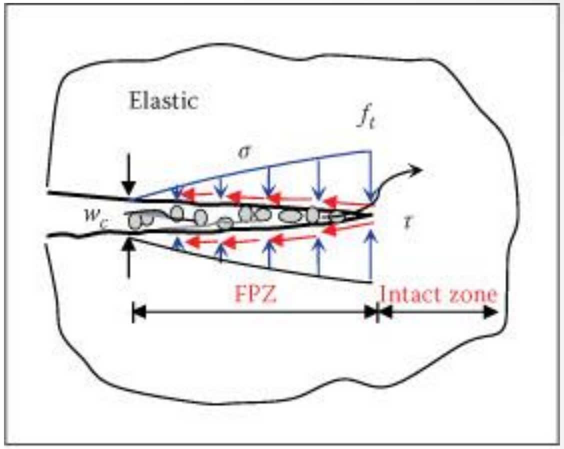
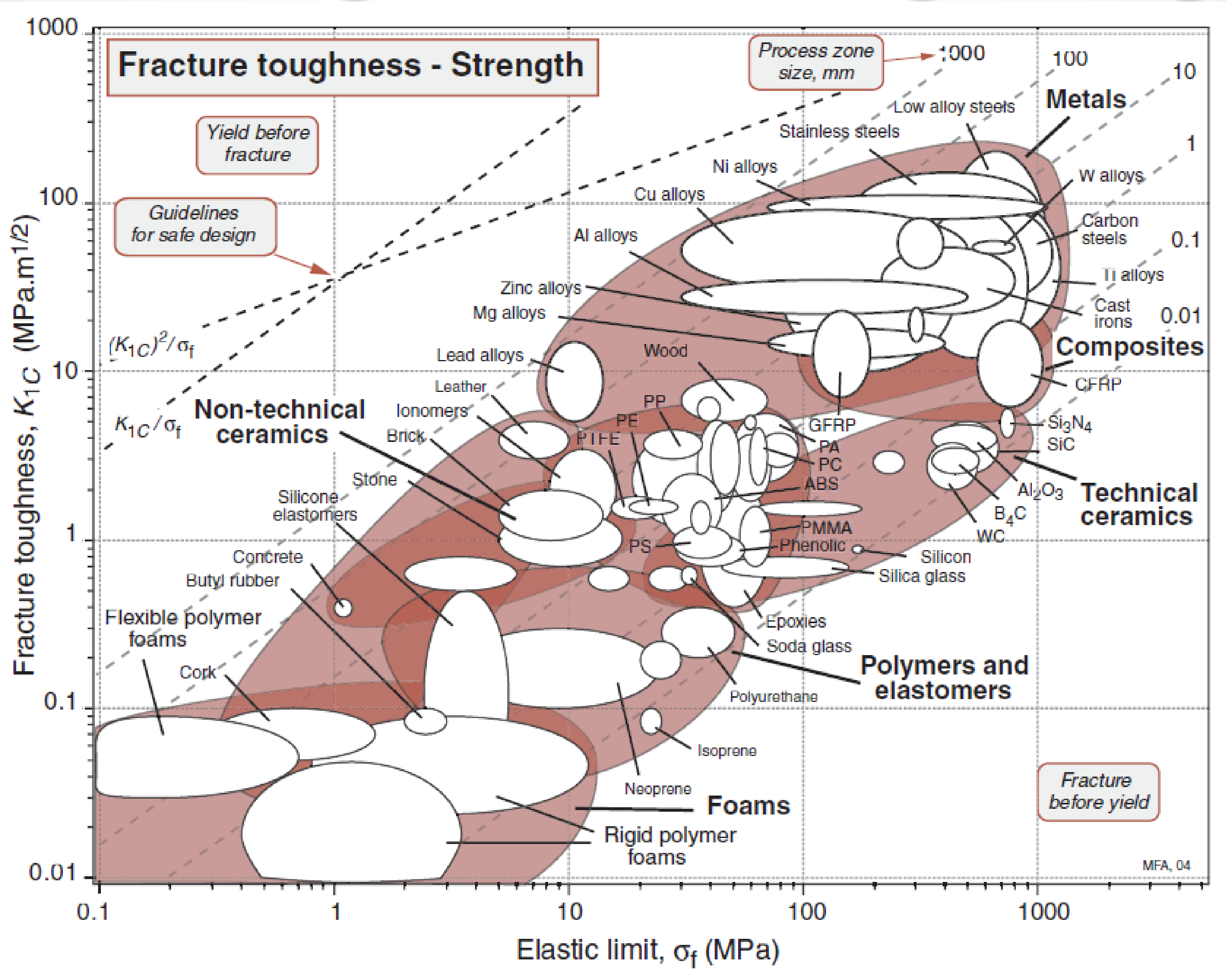


Figure 1 Normal and shear stress in the FPZ

Diagram shows the size of the zone as broken lines varying from atomic dimensions for brittle ceramics to almost 1 meter for the most ductile metals

Diagram has application in selecting materials for the safe design of load-bearing structures

Fracture Toughness vs Strength Diagram



Loss Coefficient vs Modulus Diagram

Bells are traditionally made of bronze but they can be made of glass and even of silicon carbide if enough care was taken

Metals, glasses and ceramics have low intrinsic damping or internal friction under right conditions during vibration

A large part of damping in materials is caused by dislocation movement

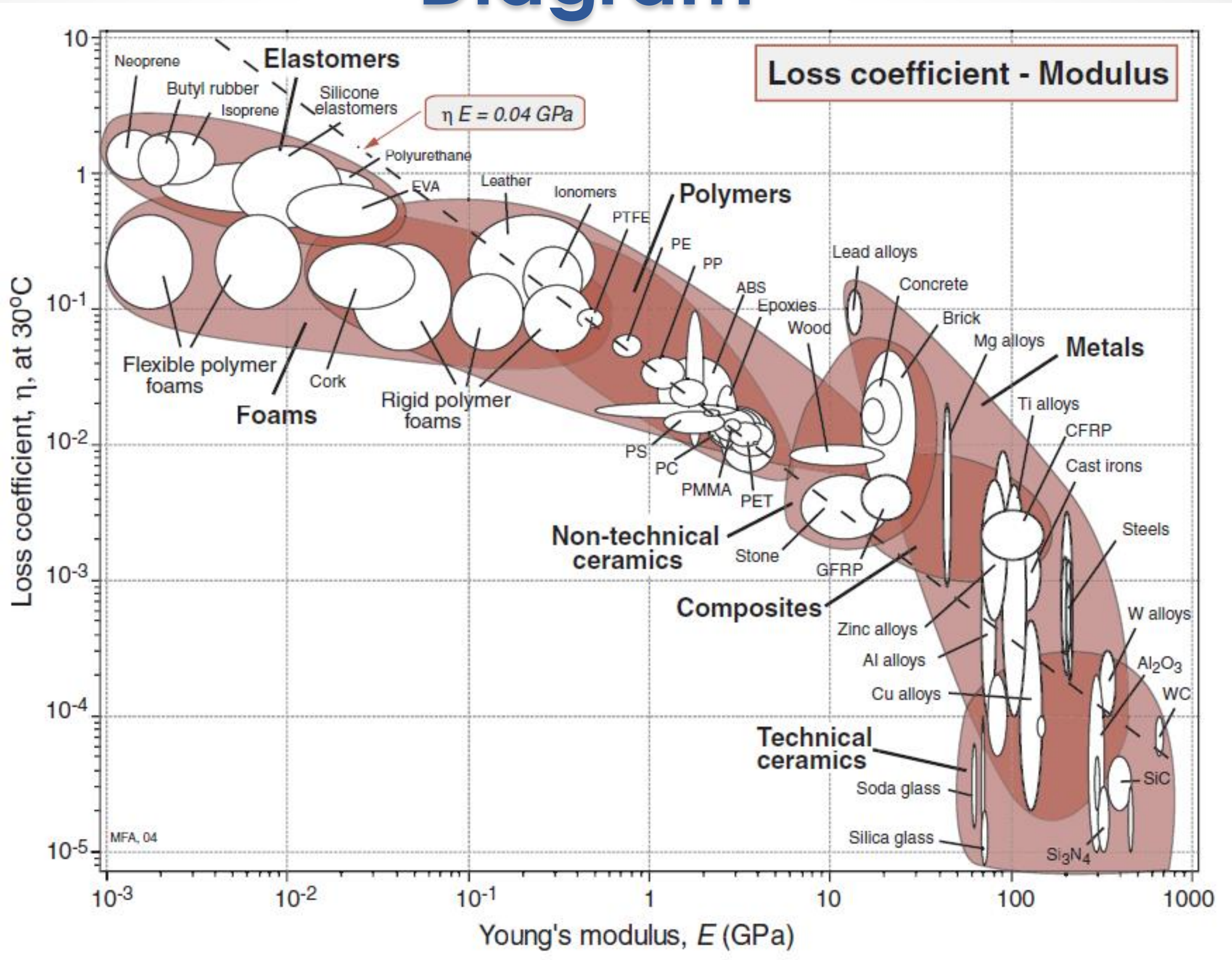
Heavily alloyed metals like bronze have low loss because the solute pins the dislocations

Engineering ceramics have low damping because of the high lattice resistance pinning dislocations

Porous ceramics are filled with cracks, the surfaces of which rub and dissipate energy when material is loaded

In polymers chain segments slide against each other when loaded and the relative motion damps energy

Loss Coefficient vs Modulus Diagram



Thermal conductivity vs Electrical resistivity Diagram

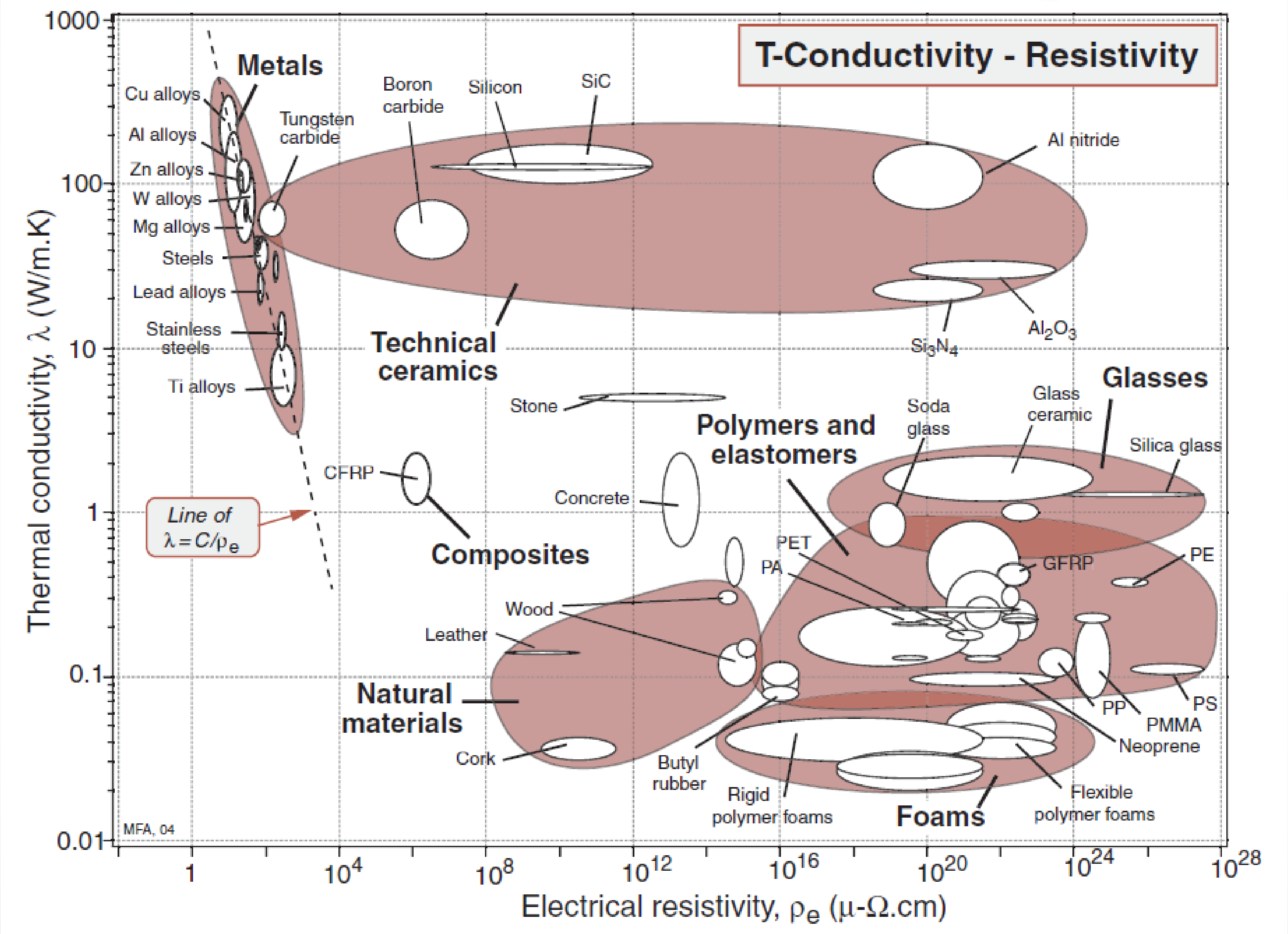
The electrons in materials carry kinetic energy and their collisions transmit this energy resulting in thermal conduction

The same electrons drift through the lattice under a potential gradient, resulting in electrical conduction

Metals have free flowing electron clouds and have high thermal and electrical conductivity

In ceramics and polymers electrons do not contribute to thermal conduction, heat is carried by lattice vibrations of short wavelength
Impurities, lattice defects and surfaces scatter the vibrations resulting in resistivity

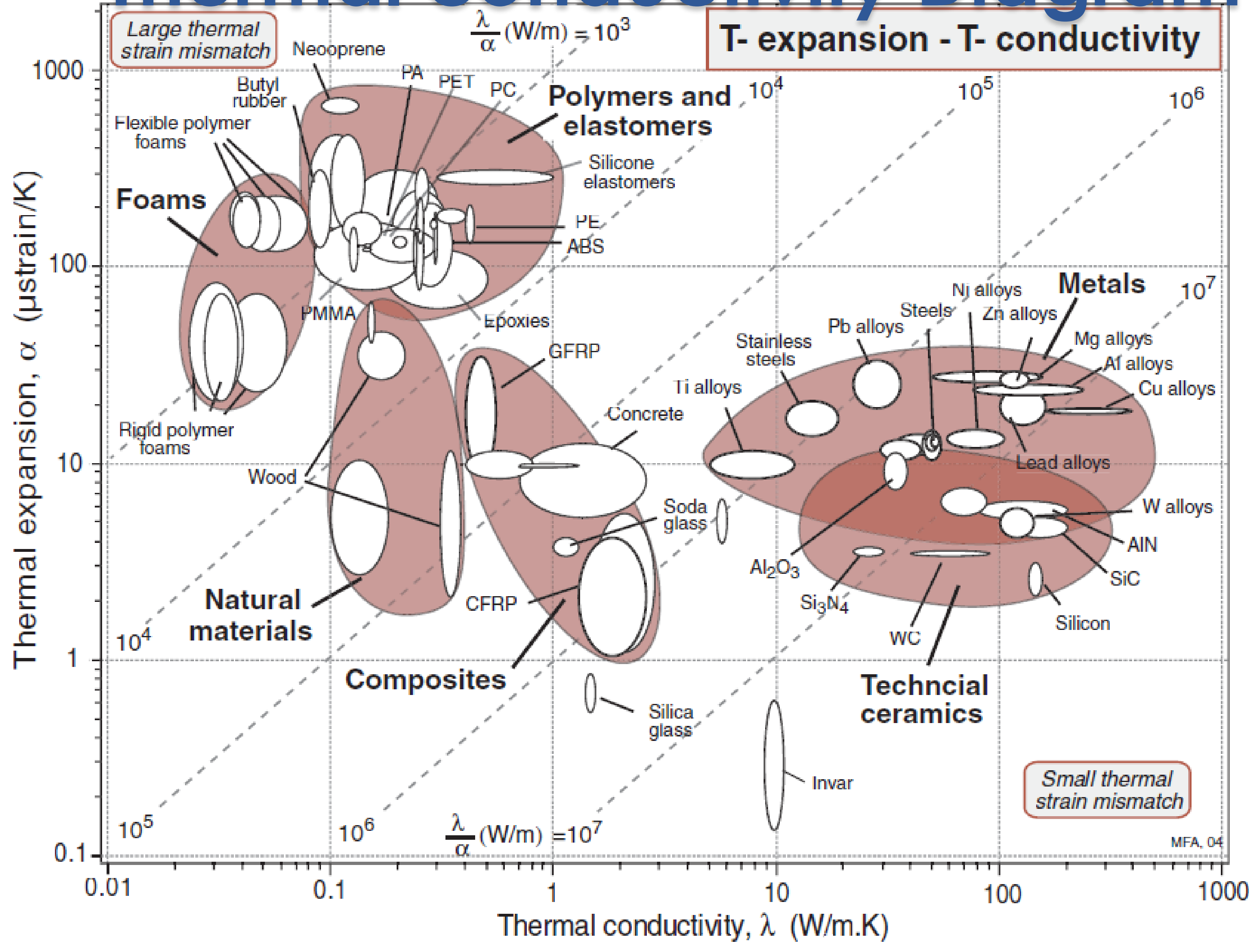
Thermal conductivity vs Electrical resistivity Diagram



Thermal expansion vs Thermal conductivity Diagram

Diagram shows contours of λ/α which is important in designing against thermal distortion

Thermal expansion vs Thermal conductivity Diagram



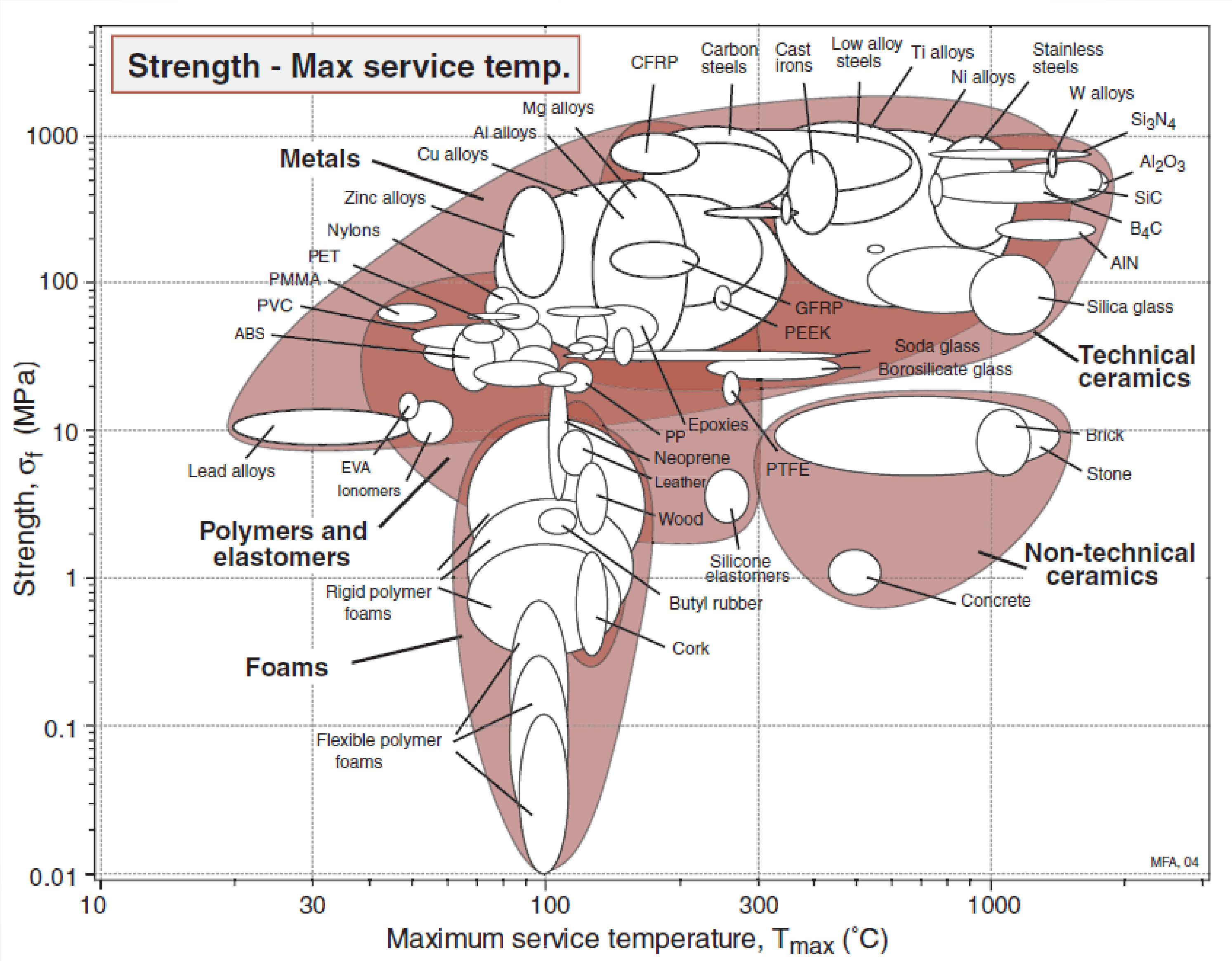
Strength vs Maximum service T Diagram

Temperature affects material performance in many ways

At high temperature materials experience creep, reduction in load bearing capacity

Chemical structure of materials change by oxidation and decomposition at high temperatures

Strength vs Maximum service T Diagram



Friction and Wear Diagrams

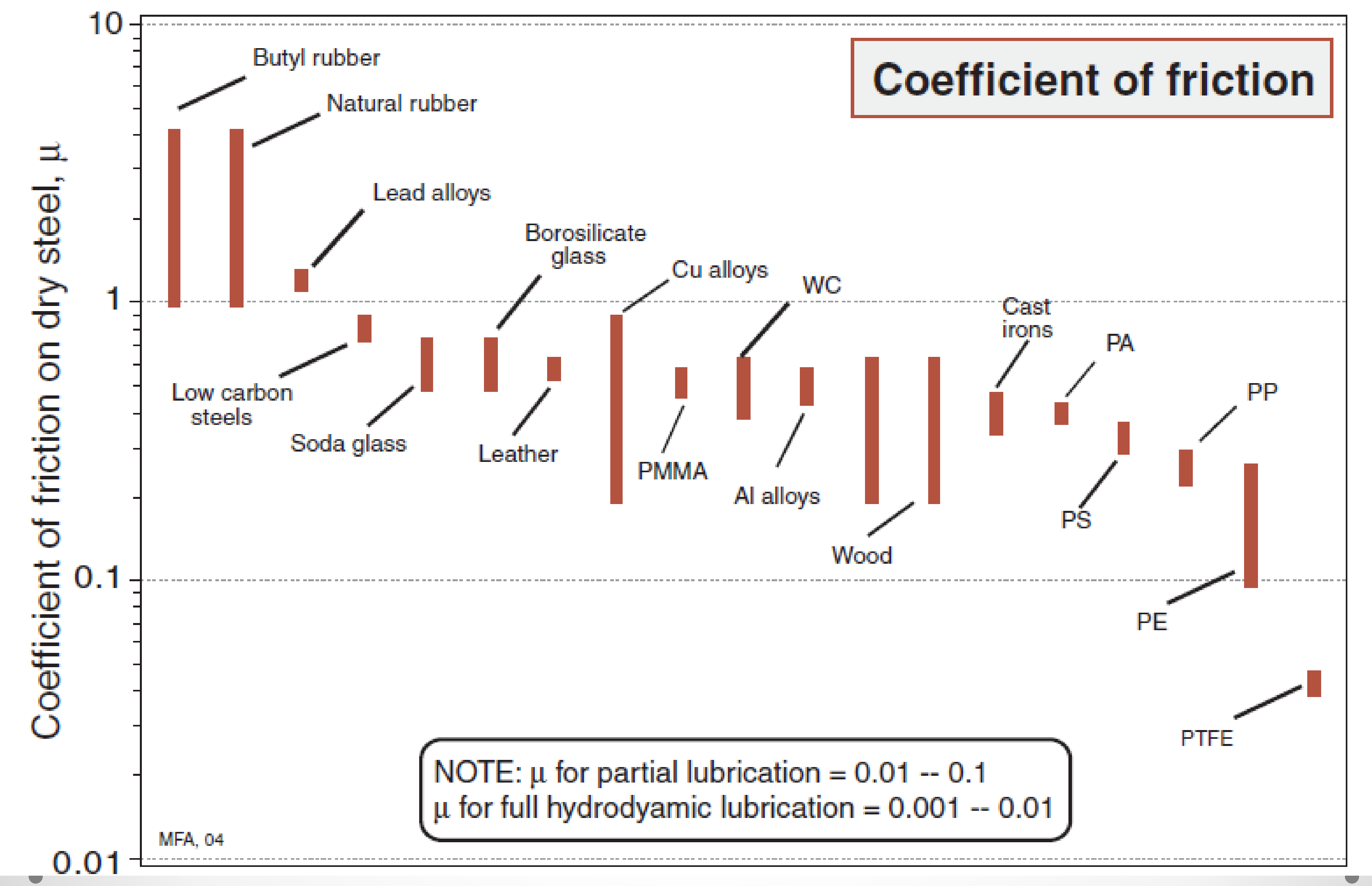
Material surfaces create many problems

When they touch and slide, there is friction and wear

The energy lost through friction and worn equipment creates an enormous cost

The efficiency of machines would be significantly improved using materials with lower coefficient of frictions

Friction and Wear Diagrams



NOTE: μ for partial lubrication = 0.01 -- 0.1
μ for full hydrodyamic lubrication = 0.001 -- 0.01

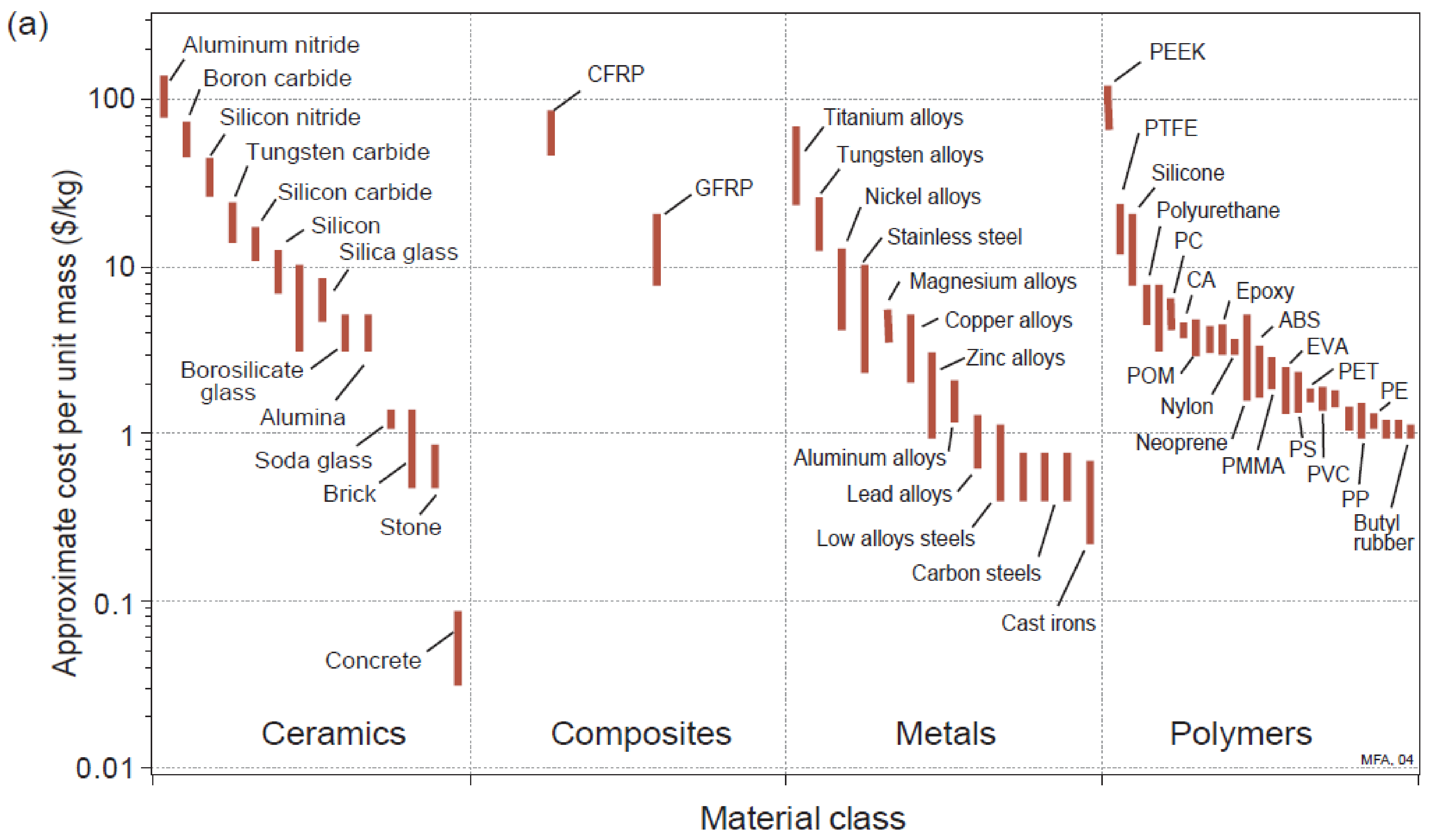
Cost Diagram

Strength, modulus or conductivity of a material do not fluctuate in time

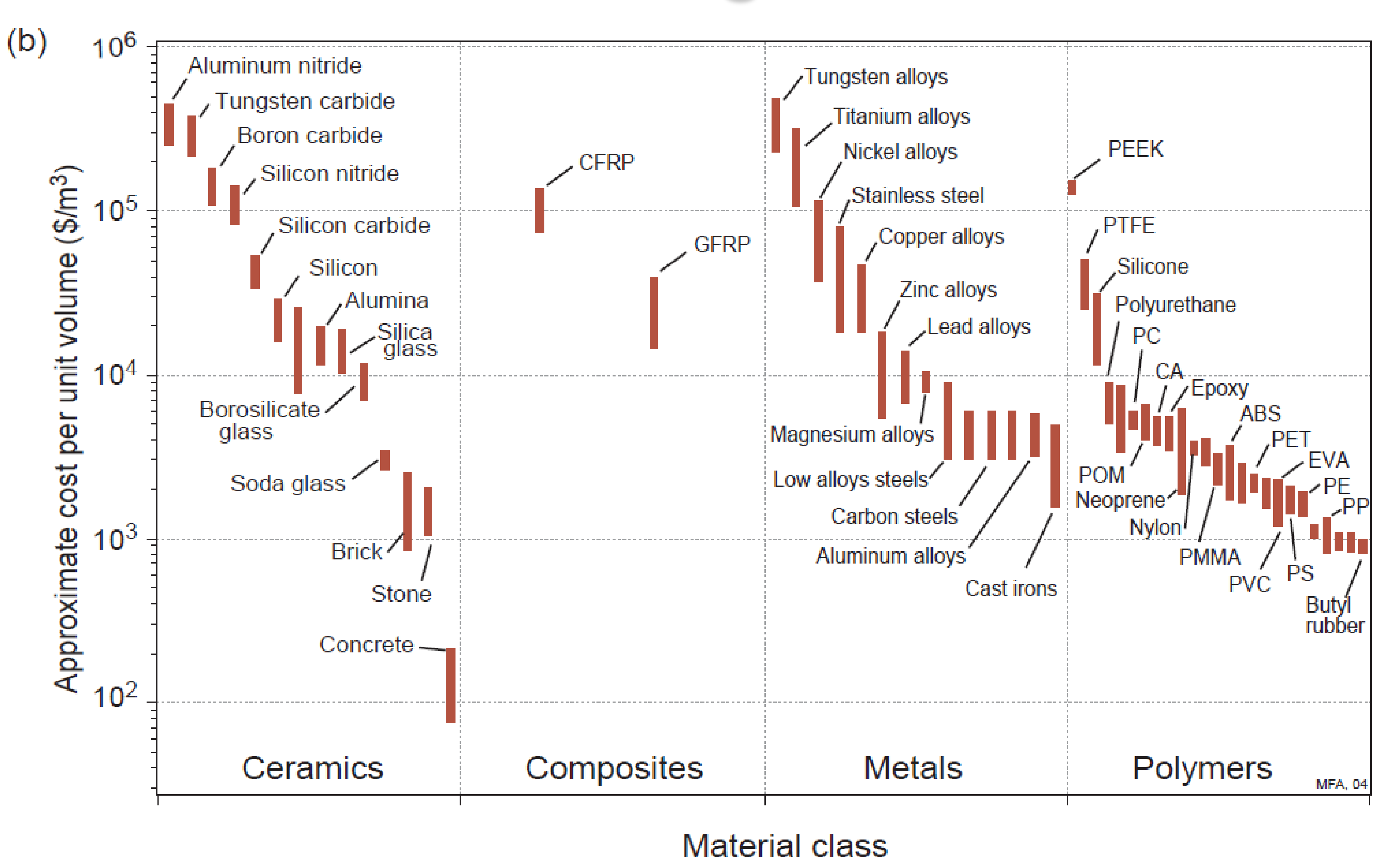
Cost on the other hand always does

The cost of commodity materials are daily reported in newspapers and internet

Cost Diagram



Cost Diagram



Modulus vs Relative cost Diagram

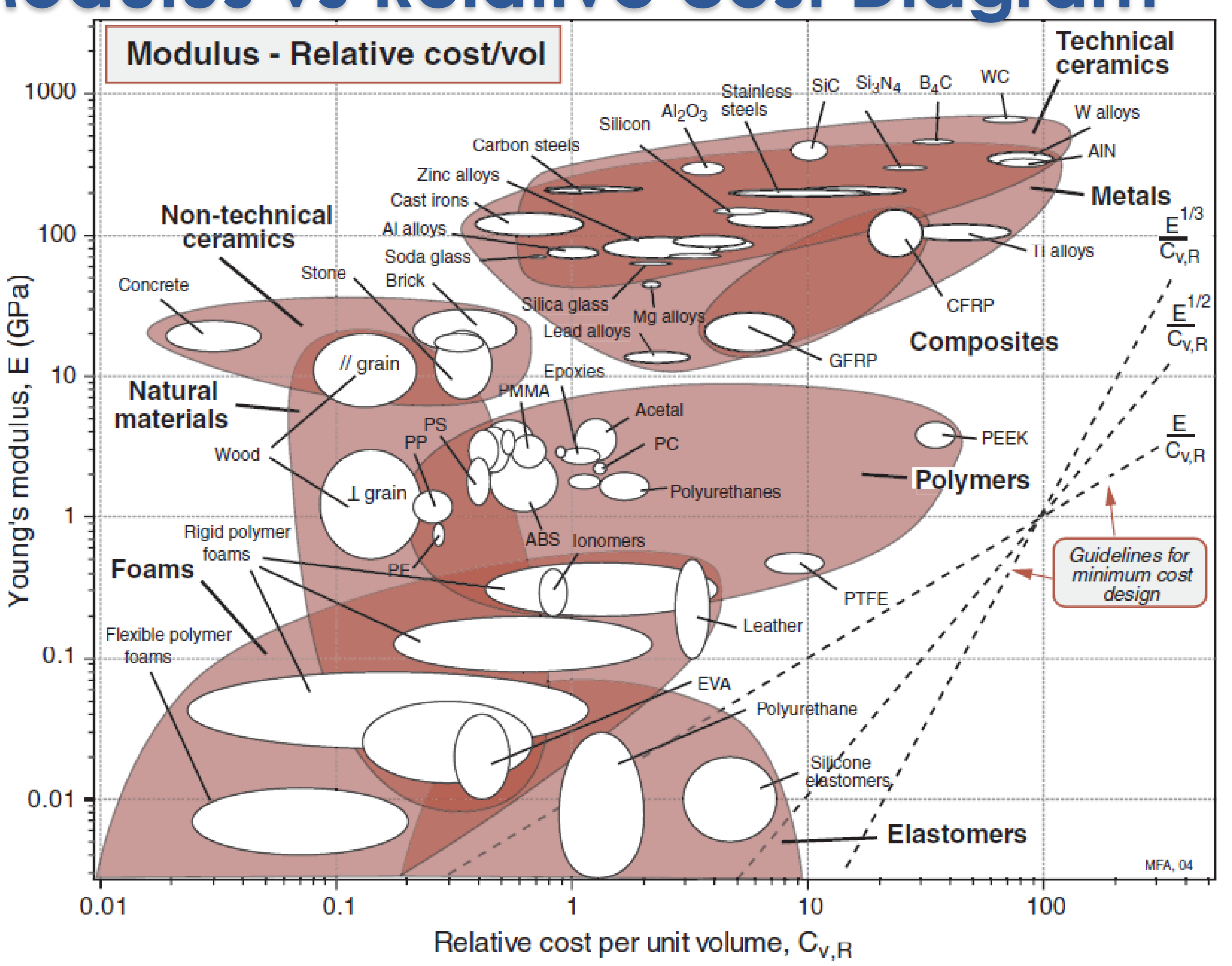
In design for minimum cost, material selection is guided by indices that involve modulus, strength and cost per unit volume

A relative cost per unit volume unit is defined to make corrections for the influence of inflation and units of currency:

$$C_{v,R} = \frac{\text{Cost/kg} \times \text{Density of material}}{\text{Cost/kg} \times \text{Density of mild steel rod}}$$

Steel rod costs about 0.3$/kg at the time of preparation of the diagrams

Modulus vs Relative cost Diagram



Strength vs Relative cost Diagram