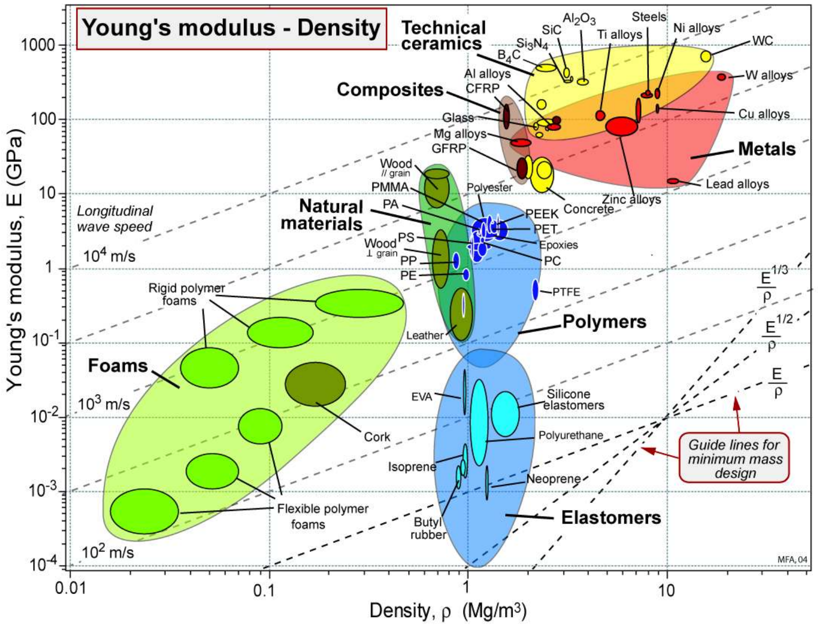

CES 2010 EDUPACK

Materials and Process Charts Compilation

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GRANTA
TEACHING RESOURCES

This compilation of Material and Process Charts is a part of a set of teaching resources created by Mike Ashby to help introduce students to materials, processes and rational selection.
The Teaching Resources website aims to support teaching of materials-related courses in Design, Engineering and Science.
Resources come in various formats and are aimed primarily at undergraduate education. Some of them are open access.

www.grantadesign.com/education/resources

Material and process charts

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Version 1

Material property charts

Introduction

The charts in this booklet summarise *material properties* and *process attributes*. Each chart appears on a single page with a brief commentary about its use. Background and data sources can be found in the book "Materials Selection in Mechanical Design" 3rd edition, by M.F. Ashby (Elsevier-Butterworth Heinemann, Oxford, 2005).

The material charts map the areas of property space occupied by each material class. They can be used in three ways:

(a) to retrieve approximate values for material properties

(b) to select materials which have prescribed property profiles

(c) to design hybrid materials.

The collection of process charts, similarly, can be used as a data source or as a selection tool. Sequential application of several charts allows several design goals to be met simultaneously. More advanced methods are described in the book cited above.

The best way to tackle selection problems is to work directly on the appropriate charts. Permission is given to copy charts for this purpose. Normal copyright restrictions apply to reproduction for other purposes.

It is not possible to give charts which plot all the possible combinations: there are too many. Those presented here are the most commonly useful. Any other can be created easily using the *CES* software[*].

Cautions. The data on the charts and in the tables are approximate: they typify each class of material (stainless steels, or polyethylenes, for instance) or processes (sand casting, or injection molding, for example), but within each class there is considerable variation. They are adequate for the broad comparisons required for conceptual design, and, often, for the rough calculations of embodiment design. **THEY ARE NOT APPROPRIATE FOR DETAILED DESIGN CALCULATIONS.** For these, it is essential to seek accurate data from handbooks and the data sheets provided by material suppliers. The charts help in narrowing the choice of candidate materials to a sensible short list, but not in providing numbers for final accurate analysis.

Every effort has been made to ensure the accuracy of the data shown on the charts. No guarantee can, however, be given that the data are error-free, or that new data may not supersede those given here. The charts are an aid to creative thinking, not a source of numerical data for precise analysis.

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[*] CES software, Granta Design (www.Grantadesign.com)

Material classes and class members

The materials of mechanical and structural engineering fall into the broad classes listed in this Table. Within each class, the Materials Selection Charts show data for a representative set of materials, chosen both to span the full range of behaviour for that class, and to include the most widely used members of it. In this way the envelope for a class (heavy lines) encloses data not only for the materials listed here but virtually all other members of the class as well. These same materials appear on all the charts.

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
Polymers (The thermoplastics and thermosets of engineering)	Acrylonitrile butadiene styrene	ABS
	Cellulose polymers	CA
	Ionomers	Ionomers
	Epoxies	Epoxy
	Phenolics	Phelonics
	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

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
Ceramics, *technical ceramics* (Fine ceramics capable of load-bearing application)	Alumina	Al_20_3
	Aluminum nitride	AlN
	Boron carbide	B_4C
	Silicon Carbide	SiC
	Silicon Nitride	Si_3N_4
	Tungsten carbide	WC
Ceramics, *non-technical ceramics* (Porous ceramics of construction)	Brick	Brick
	Concrete	Concrete
	Stone	Stone
Glasses	Soda-lime glass	Soda-lime glass
	Borosilicate glass	Borosilicate
	Silica glass	Silica glass
	Glass ceramic	Glass ceramic
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

You will not find specific material grades on the charts. The aluminum alloy 7075 in the T6 condition (for instance) is contained in the property envelopes for *Al-alloys*; the Nylon 66 in those for *nylons*. The charts are designed for the broad, early stages of materials selection, not for retrieving the precise values of properties needed in the later, detailed design, stage.

Material properties

The charts that follow display the properties listed here. The charts let you pick off the subset of materials with a property within a specified range: materials with modulus E between 100 and 200 GPa for instance; or materials with a thermal conductivity above 100 W/mK.

Frequently, performance is maximized by selecting the subset of materials with the greatest value of a grouping of material properties. A light, stiff beam is best made of a material with a high value of $E^{1/2}/\rho$; safe pressure vessels are best made of a material with a high value of $K_{1c}^{1/2}/\sigma_f$, and so on. The Charts are designed to display these groups or "material indices", and to allow you to pick off the subset of materials which maximize them. The Appendix of this document lists material indices. Details of the method, with worked examples, are given in "Materials Selection in Mechanical Design", cited earlier.

Multiple criteria can be used. You can pick off the subset of materials with both high $E^{1/2}/\rho$ *and* high E (good for light, stiff beams) from Chart 1; that with high σ_f^2/E^3 and high E (good materials for pivots) from Chart 4. Throughout, the goal is to identify from the Charts a *subset* of materials, not a single material. Finding the best material for a given application involves many considerations, many of them (like availability, appearance and feel) not easily quantifiable. The Charts do not give you the final choice - that requires the use of your judgement and experience. Their power is that they guide you quickly and efficiently to a subset of materials worth considering; and they make sure that you do not overlook a promising candidate.

Class	Property	Symbol and Units
General	Density Price	ρ (kg/m^3 or Mg/m^3) C_m (\$/kg)
Mechanical	Elastic moduli (Young's, Shear, Bulk) Yield strength Ultimate strength Compressive strength Failure strength Hardness Elongation Fatigue endurance limit Fracture toughness Toughness Loss coefficient (damping capacity)	E, G, K (GPa) σ_y (MPa) σ_u (MPa) σ_c (MPa) σ_f (MPa) H (Vickers) ε (--) σ_e (MPa) K_{1c} (MPa.m$^{1/2}$) G_{1c} (kJ/m^2) η (--)
Thermal	Melting point Glass temperature Maximum service temperature Thermal conductivity Specific heat Thermal expansion coefficient Thermal shock resistance	T_m (C or K) T_g (C or K) T_{max} (C or K) λ (W/m.K) C_p (J/kg.K) α (°K^{-1}) ΔT_s (C or K)
Electrical	Electrical resistivity Dielectric constant	ρ_e (Ω.m or $\mu\Omega$.cm)) ε_d (--)
Eco-properties	Energy/kg to extract material	E_f (MJ/kg)
Environmental resistance	Wear rate constant	K_A MPa^{-1}

Chart 1: Young's modulus, E and Density, ρ

This chart guides selection of materials for light, stiff, components. The moduli of engineering materials span a range of 10^7; the densities span a range of 3000. The contours show the longitudinal wave speed in m/s; natural vibration frequencies are proportional to this quantity. The guide lines show the loci of points for which

- $E/\rho = C$ (minimum weight design of stiff ties; minimum deflection in centrifugal loading, etc)
- $E^{1/2}/\rho = C$ (minimum weight design of stiff beams, shafts and columns)
- $E^{1/3}/\rho = C$ (minimum weight design of stiff plates)

The value of the constant C increases as the lines are displaced upwards and to the left; materials offering the greatest stiffness-to-weight ratio lie towards the upper left hand corner. Other moduli are obtained approximately from E using

- $\nu = 1/3$; $G = 3/8E$; $K \approx E$ (metals, ceramics, glasses and glassy polymers)
- or $\nu \approx 0.5$; $G \approx E/3$; $K \approx 10E$ (elastomers, rubbery polymers)

where ν is Poisson's ratio, G the shear modulus and K the bulk modulus.

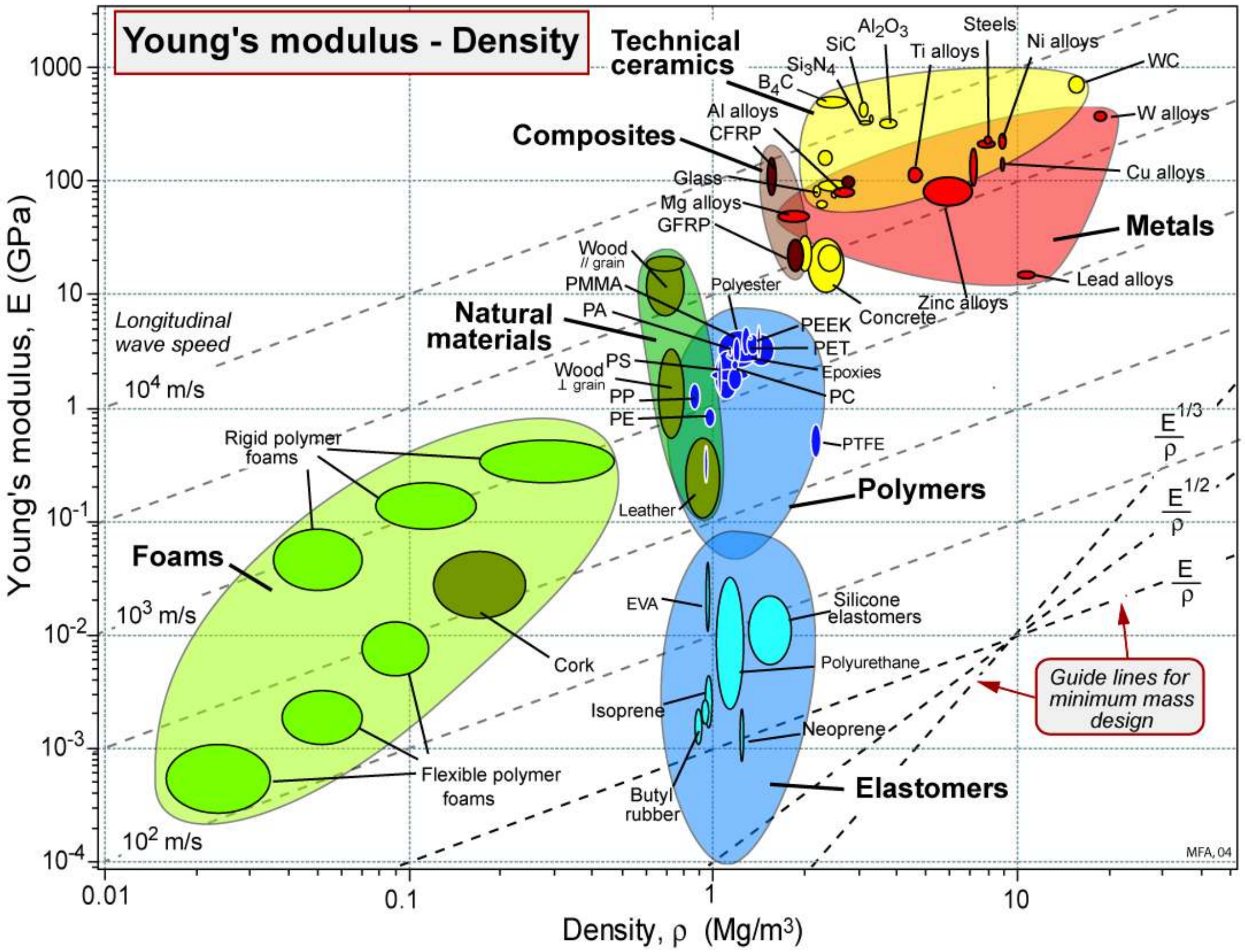


Chart 2: Strength, σ_f against Density, ρ

This is the chart for designing light, strong structures. The "strength" for metals is the 0.2% offset yield strength. For polymers, it is the stress at which the stress-strain curve becomes markedly non-linear - typically, a strain of abut 1%. For ceramics and glasses, it is the compressive crushing strength; remember that this is roughly 15 times larger than the tensile (fracture) strength. For composites it is the tensile strength. For elastomers it is the tear-strength. The chart guides selection of materials for light, strong, components. The guide lines show the loci of points for which:

(a) $\sigma_f/\rho = C$ (minimum weight design of strong ties; maximum rotational velocity of disks)

(b) $\sigma_f^{2/3}/\rho = C$ (minimum weight design of strong beams and shafts)

(c) $\sigma_f^{1/2}/\rho = C$ (minimum weight design of strong plates)

The value of the constant C increases as the lines are displaced upwards and to the left. Materials offering the greatest strength-to-weight ratio lie towards the upper left corner.

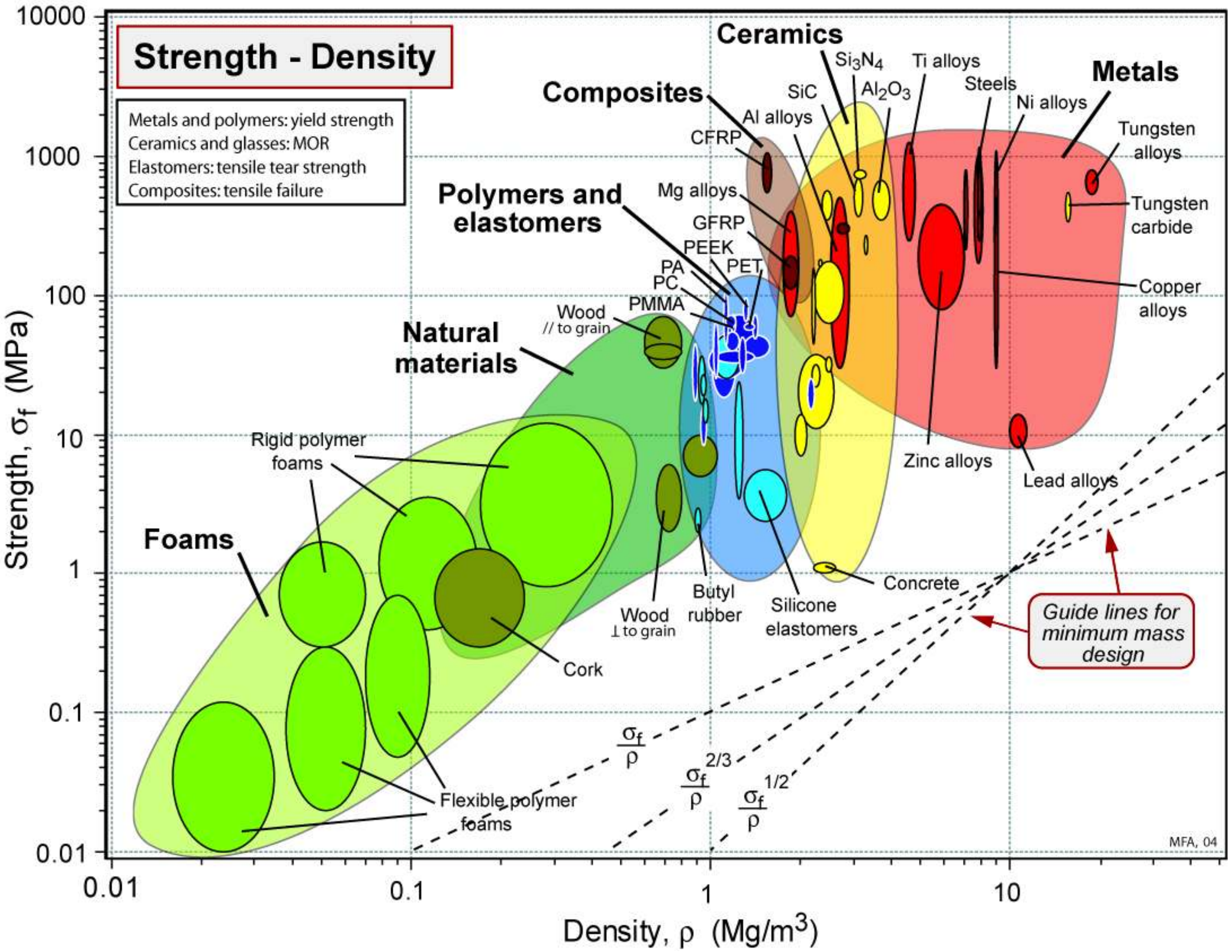


Chart 3: Young's modulus, E, against Strength, σ_f

The chart for elastic design. The "strength" for metals is the 0.2% offset yield strength. For polymers, it is the 1% yield strength. For ceramics and glasses, it is the compressive crushing strength; remember that this is roughly 15 times larger than the tensile (fracture) strength. For composites it is the tensile strength. For elastomers it is the tear-strength. The chart has numerous applications among them: the selection of materials for springs, elastic hinges, pivots and elastic bearings, and for yield-before-buckling design. The contours show the failure strain, σ_f / E. The guide lines show three of these; they are the loci of points for which:

(a) $\sigma_f /E = C$ (elastic hinges)

(b) $\sigma_f^2 /E = C$ (springs, elastic energy storage per unit volume)

(c) $\sigma_f^{3/2}/E = C$ (selection for elastic constants such as knife edges; elastic diaphragms, compression seals)

The value of the constant C increases as the lines are displaced downward and to the right.

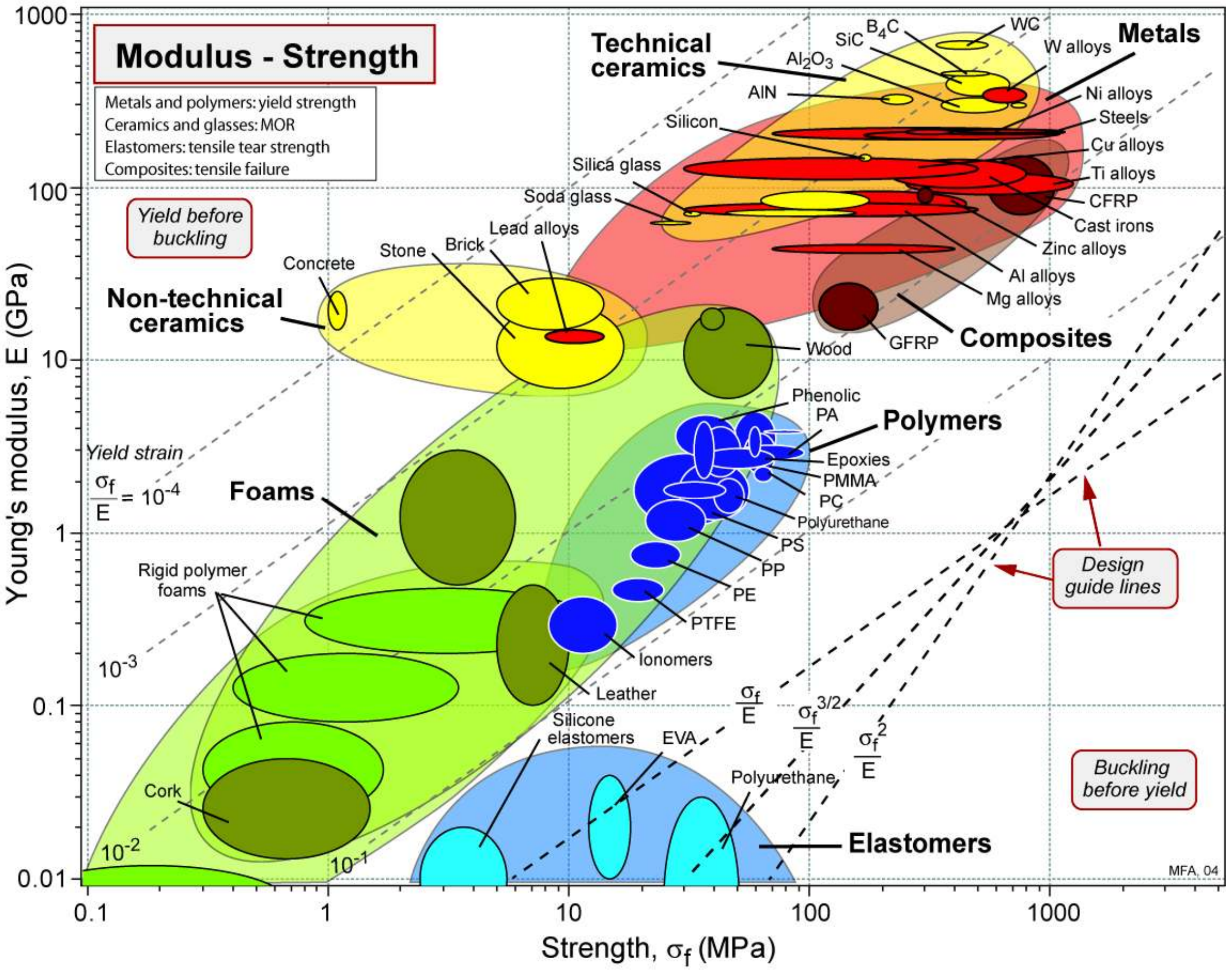


Chart 4: Specific modulus, E/ρ, against Specific strength, σ_f/ρ

The chart for specific stiffness and strength. The contours show the yield strain, σ_f/E. The qualifications on strength given for Charts 2 and 4 apply here also. The chart finds application in minimum weight design of ties and springs, and in the design of rotating components to maximize rotational speed or energy storage, etc. The guide lines show the loci of points for which

(a) $\sigma_f^2/E\rho = C$ (ties, springs of minimum weight; maximum rotational velocity of disks)

(b) $\sigma_f^{2/3}/E\rho^{1/2} = C$

(c) $\sigma_f/E = C$ (elastic hinge design)

The value of the constant C increases as the lines are displaced downwards and to the right.

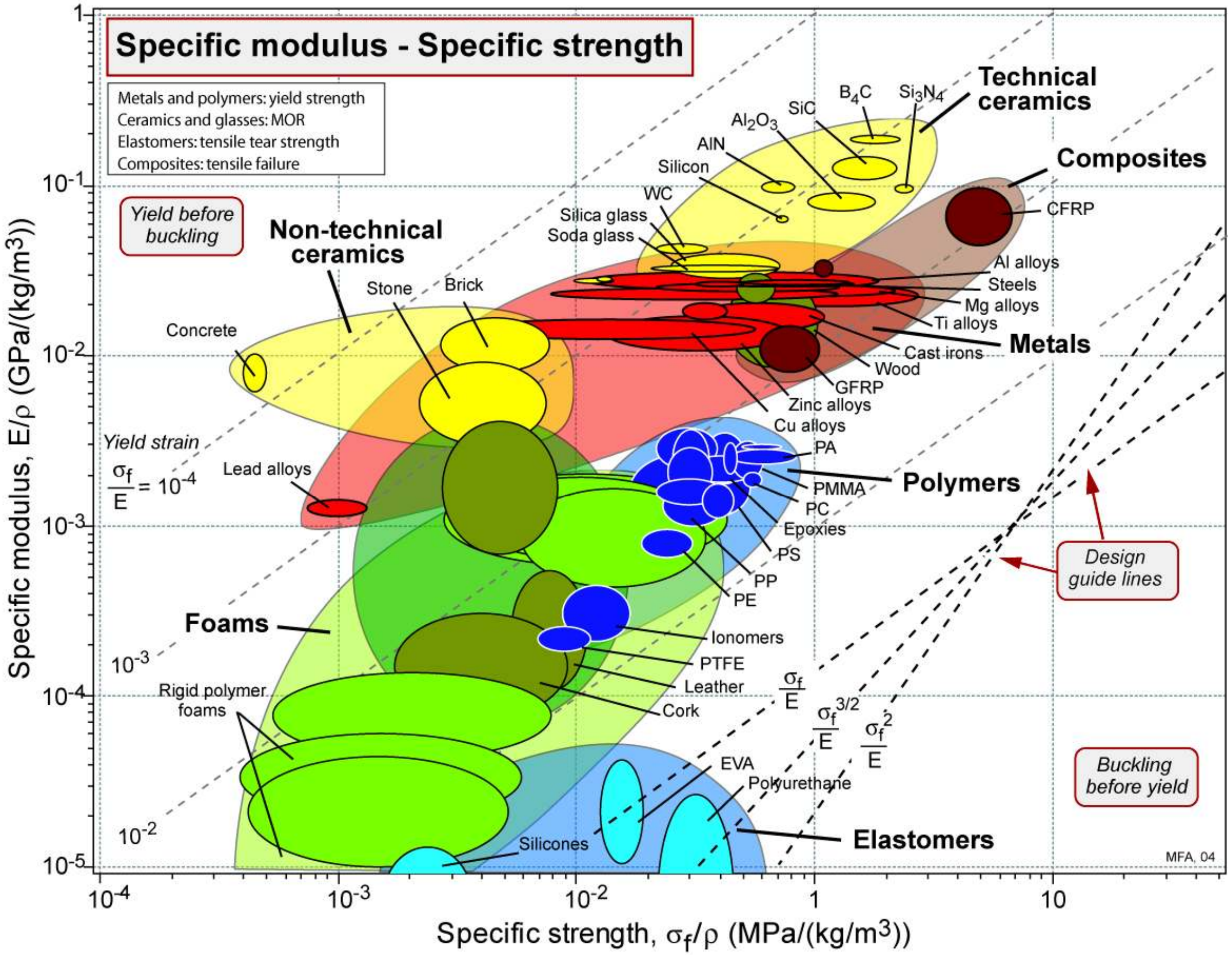


Chart 5: Fracture toughness, K_{Ic}, against Young's modulus, E

The chart displays both the fracture toughness, K_{1c}, and (as contours) the toughness, $G_{1c} \approx K_{1c}^2 / E$. It allows criteria for stress and displacement-limited failure criteria (K_{1c} and K_{1c} / E) to be compared. The guidelines show the loci of points for which

(a) $K_{Ic}^2 / E = C$ (lines of constant toughness, G_c; energy-limited failure)

(b) $K_{Ic} / E = C$ (guideline for displacement-limited brittle failure)

The values of the constant C increases as the lines are displaced upwards and to the left. Tough materials lie towards the upper left corner, brittle materials towards the bottom right.

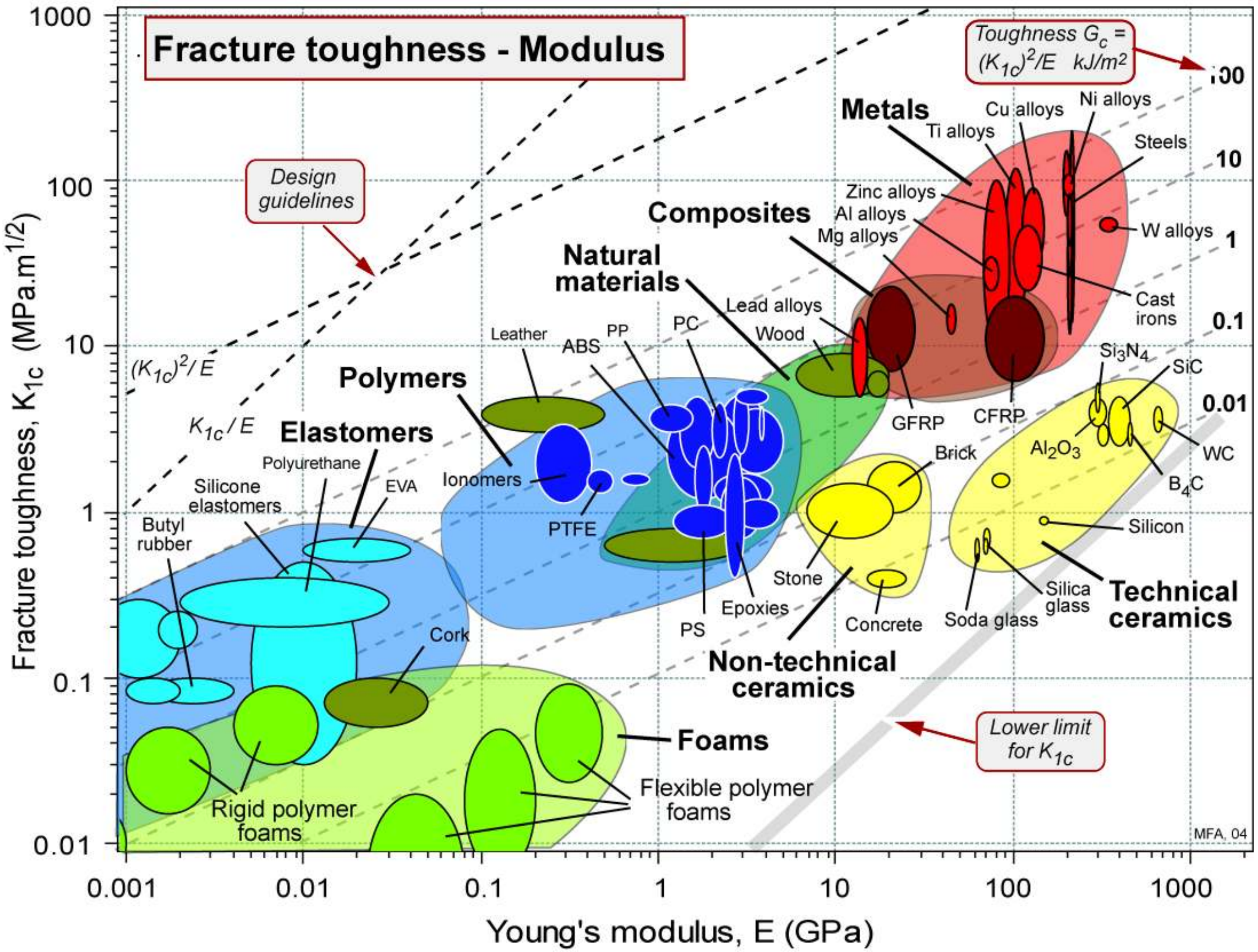


Chart 6: Fracture toughness, K_{Ic}, against Strength, σ_f

The chart for safe design against fracture. The contours show the process-zone diameter, given approximately by $K_{Ic}^2/\pi\sigma_f^2$. The qualifications on "strength" given for Charts 2 and 3 apply here also. The chart guides selection of materials to meet yield-before-break design criteria, in assessing plastic or process-zone sizes, and in designing samples for valid fracture toughness testing. The guide lines show the loci of points for which

(a) $K_{Ic}/\sigma_f = C$ (yield-before-break)

(b) $K_{Ic}^2/\sigma_f = C$ (leak-before-break)

The value of the constant C increases as the lines are displaced upward and to the left.

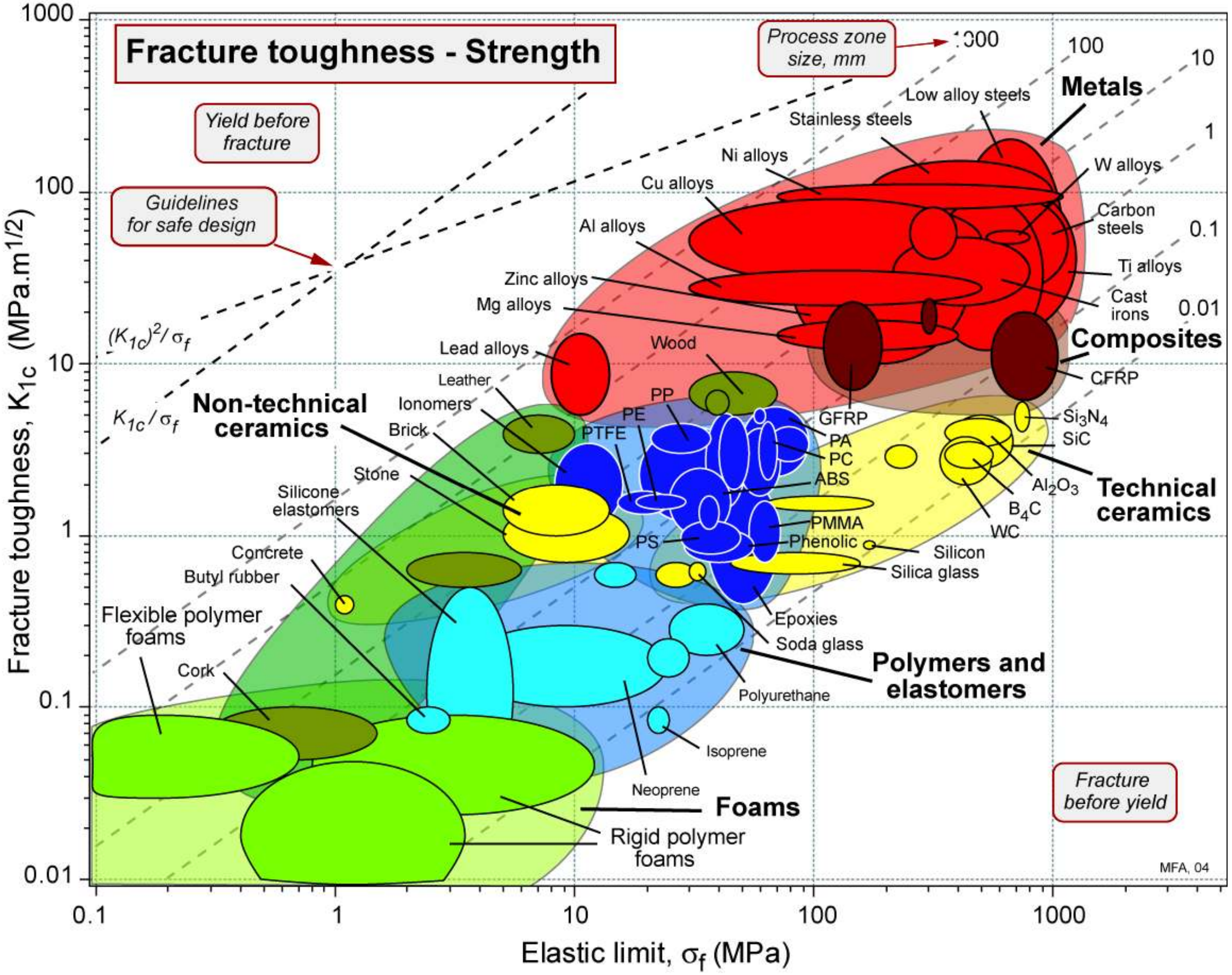


Chart 7: Loss coefficient, η, against Young's modulus, E

The chart gives guidance in selecting material for low damping (springs, vibrating reeds, etc) and for high damping (vibration-mitigating systems). The guide line shows the loci of points for which

(a) $\eta E = C$ (rule-of-thumb for estimating damping in polymers)

The value of the constant C increases as the line is displaced upward and to the right.

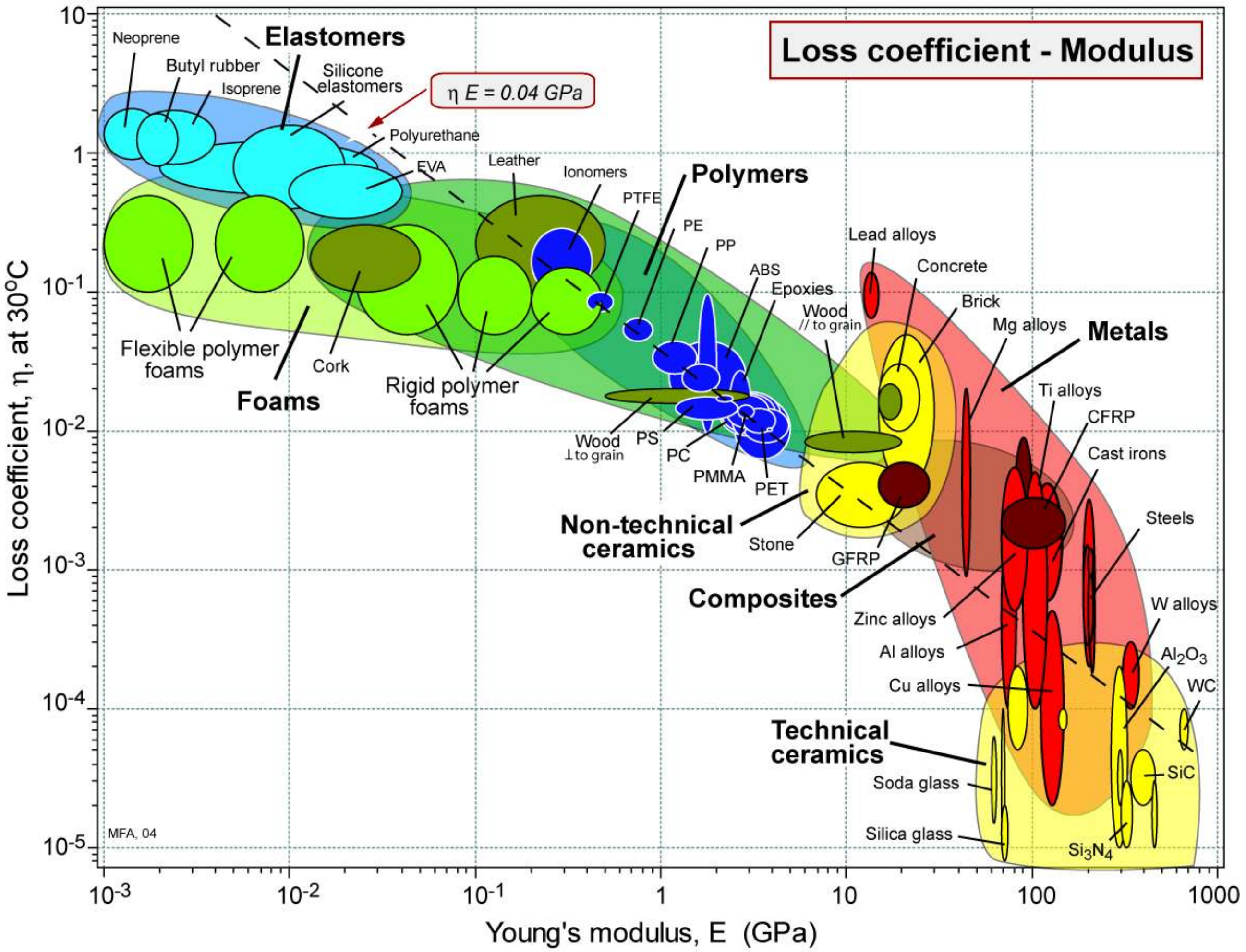


Chart 8: Thermal conductivity, λ, against Electrical conductivity, ρ_e

This is the chart for exploring thermal and electrical conductivies (the electrical conductivity κ is the reciprocal of the resistivity ρ_e). For metals the two are proportional (the Wiedemann-Franz law):

$$\lambda \approx \kappa = \frac{1}{\rho_e}$$

because electronic contributions dominate both. But for other classes of solid thermal and electrical conduction arise from different sources and the correlation is lost.

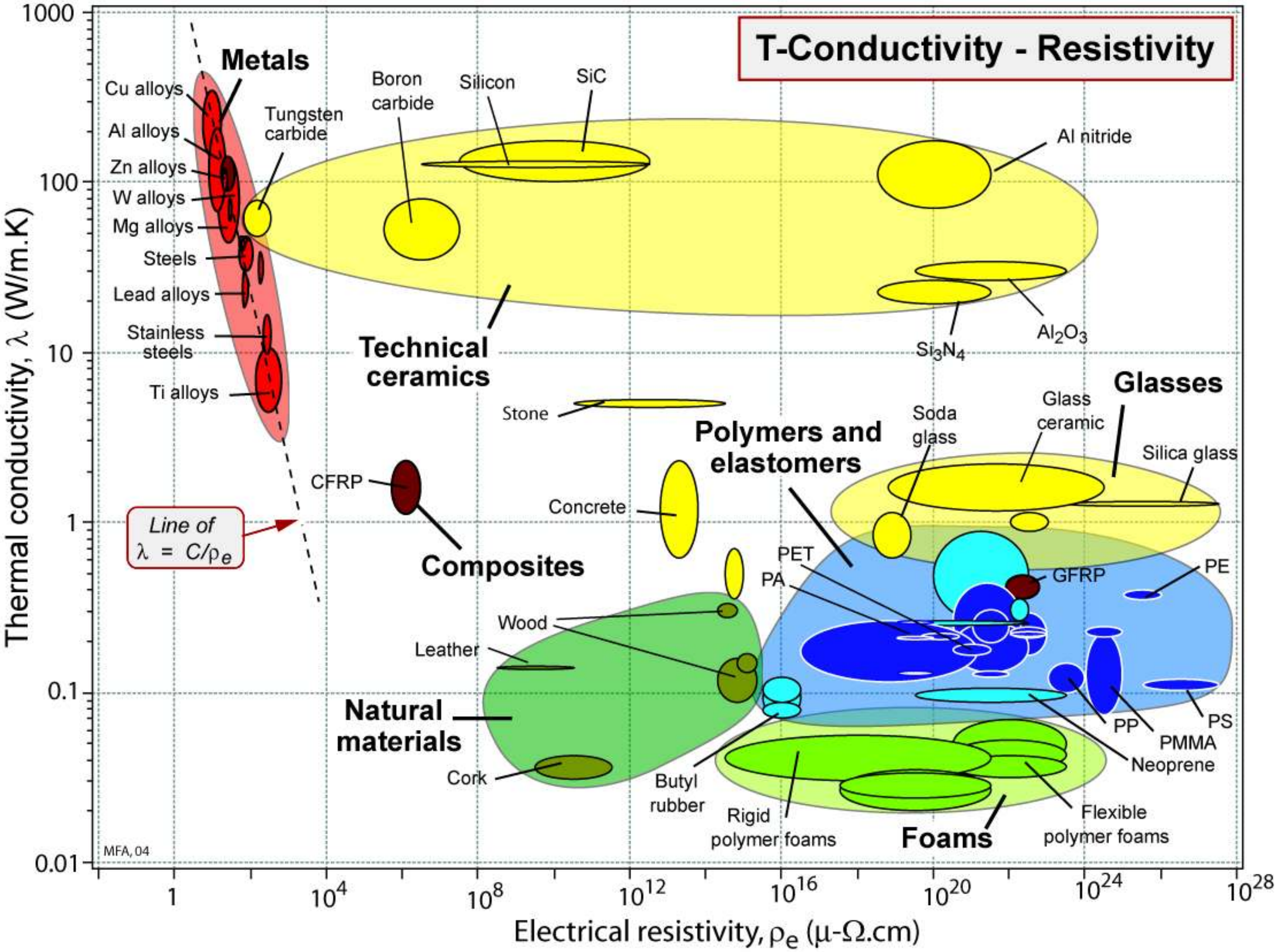


Chart 9: Thermal conductivity, λ, against Thermal diffusivity, *a*

The chart guides in selecting materials for thermal insulation, for use as heat sinks and such like, both when heat flow is steady, (λ) and when it is transient (thermal diffusivity $a = \lambda/\rho C_p$ where ρ is the density and C_p the specific heat). Contours show values of the volumetric specific heat, $\rho C_p = \lambda/a$ (J/m^{3}K). The guidelines show the loci of points for which

(a) $\lambda/a = C$ (constant volumetric specific heat)

(b) $\lambda/a^{1/2} = C$ (efficient insulation; thermal energy storage)

The value of constant C increases towards the upper left.

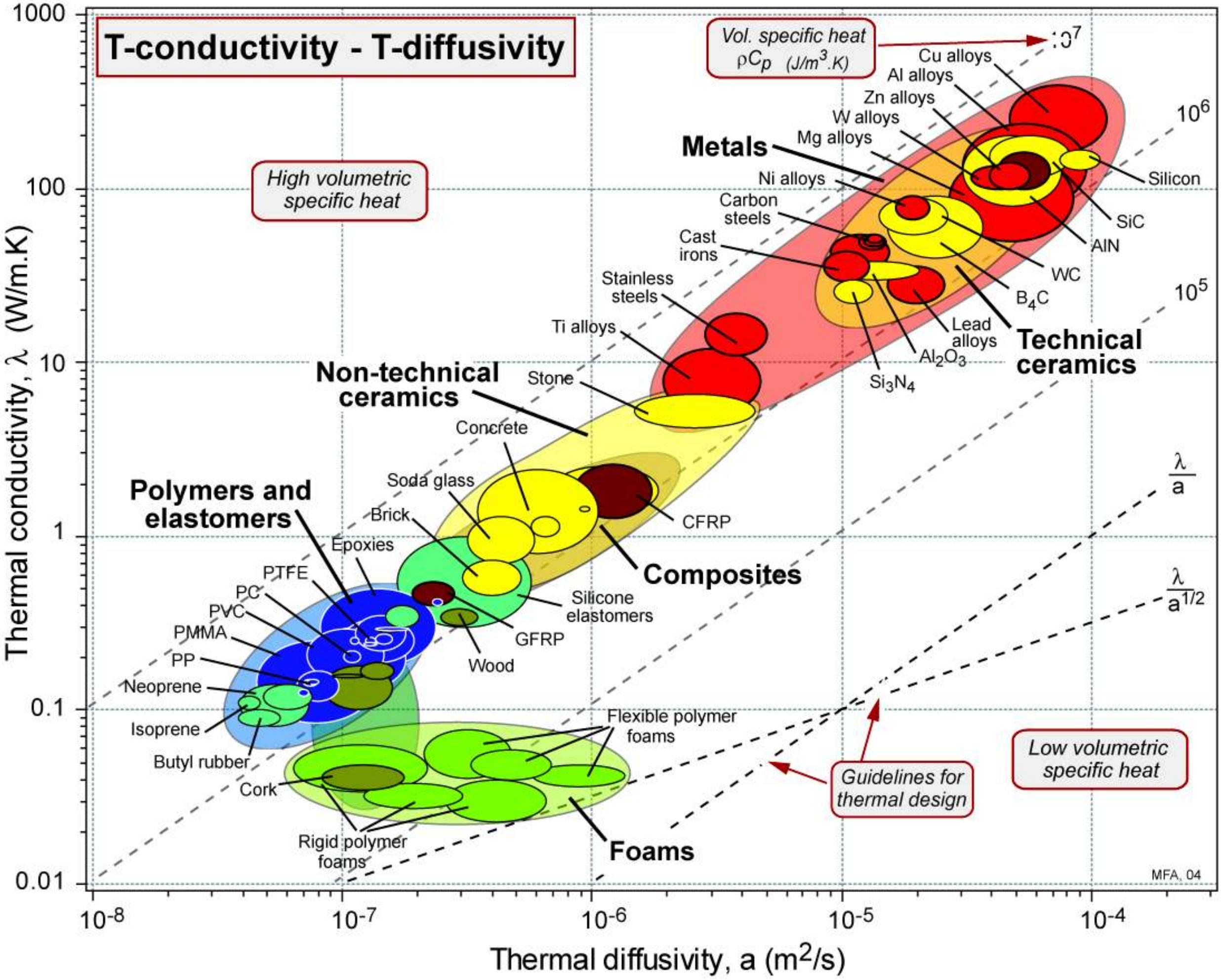


Chart 10: Thermal expansion coefficient, α, against Thermal conductivity, λ

The chart for assessing thermal distortion. The contours show value of the ratio λ/α (W/m). Materials with a large value of this design index show small thermal distortion. They define the guide line

(a) $\lambda/\alpha = C$ (minimization of thermal distortion)

The value of the constant C increases towards the bottom right.

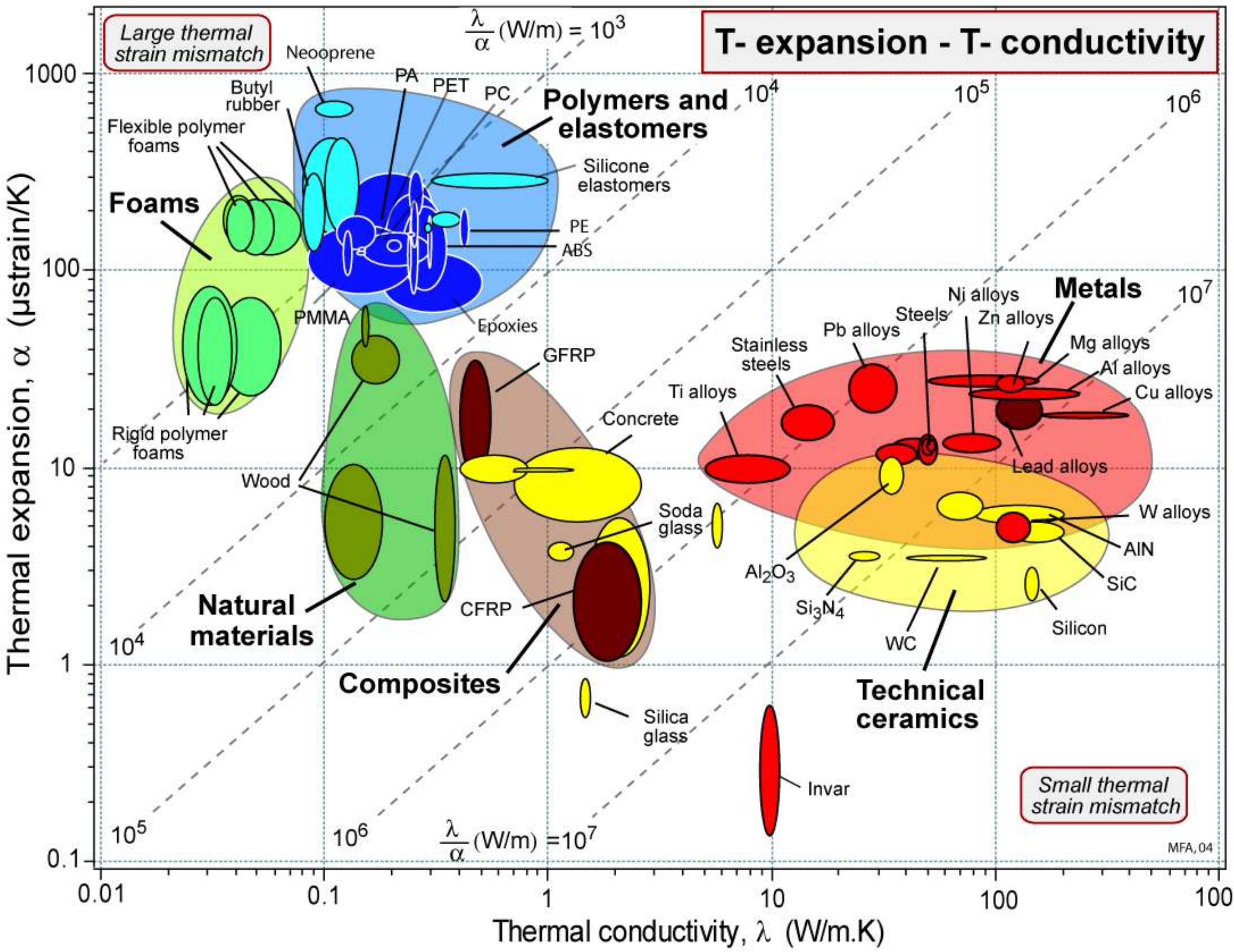


Chart 11: Linear thermal expansion, α, against Young's modulus, E

The chart guides in selecting materials when thermal stress is important. The contours show the thermal stress generated, per ^{o}C temperature change, in a constrained sample. They define the guide line

$\alpha E = C$ MPa/K (constant thermal stress per ^{o}K)

The value of the constant C increases towards the upper right.

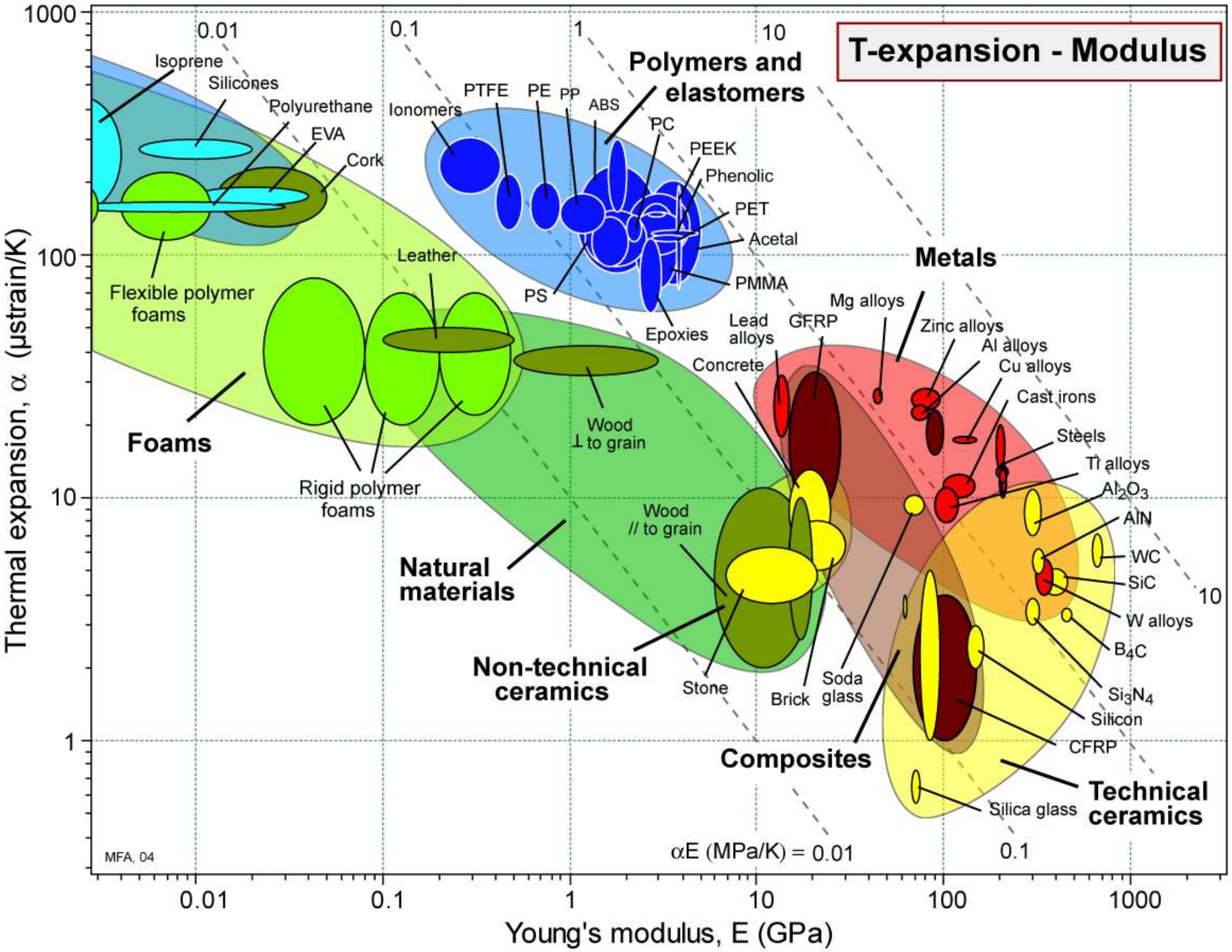


Chart 12: Strength, σ_f, against Maximum service temperature T_{max}

Temperature affects material performance in many ways. As the temperature is raised the material may creep, limiting its ability to carry loads. It may degrade or decompose, changing its chemical structure in ways that make it unusable. And it may oxidise or interact in other ways with the environment in which it is used, leaving it unable to perform its function. The approximate temperature at which, for any one of these reasons, it is unsafe to use a material is called its *maximum service temperature* T_{max}. Here it is plotted against strength σ_f.

The chart gives a birds-eye view of the regimes of stress and temperature in which each material class, and material, is usable. Note that even the best polymers have little strength above 200°C; most metals become very soft by 800°C; and only ceramics offer strength above 1500°C.

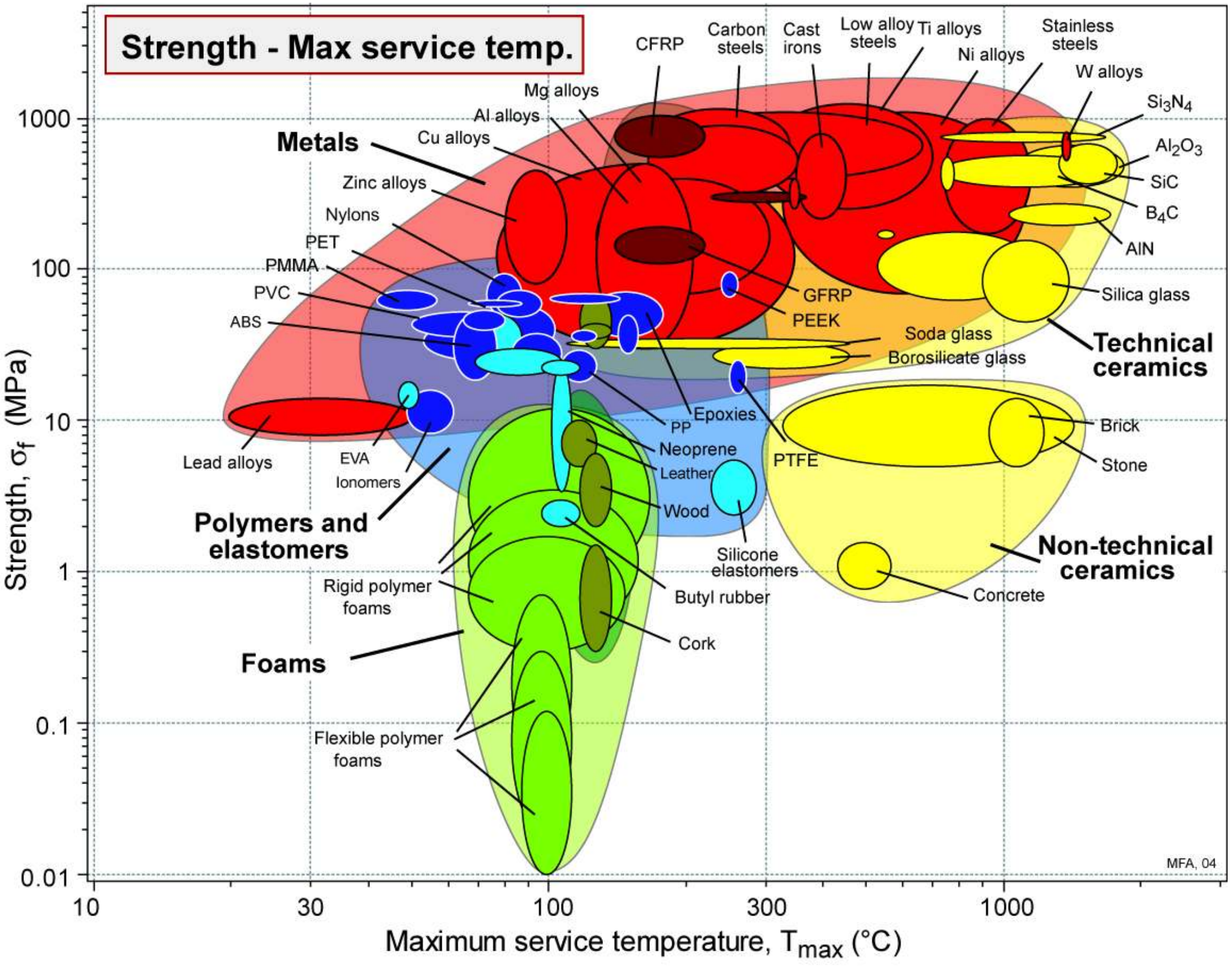
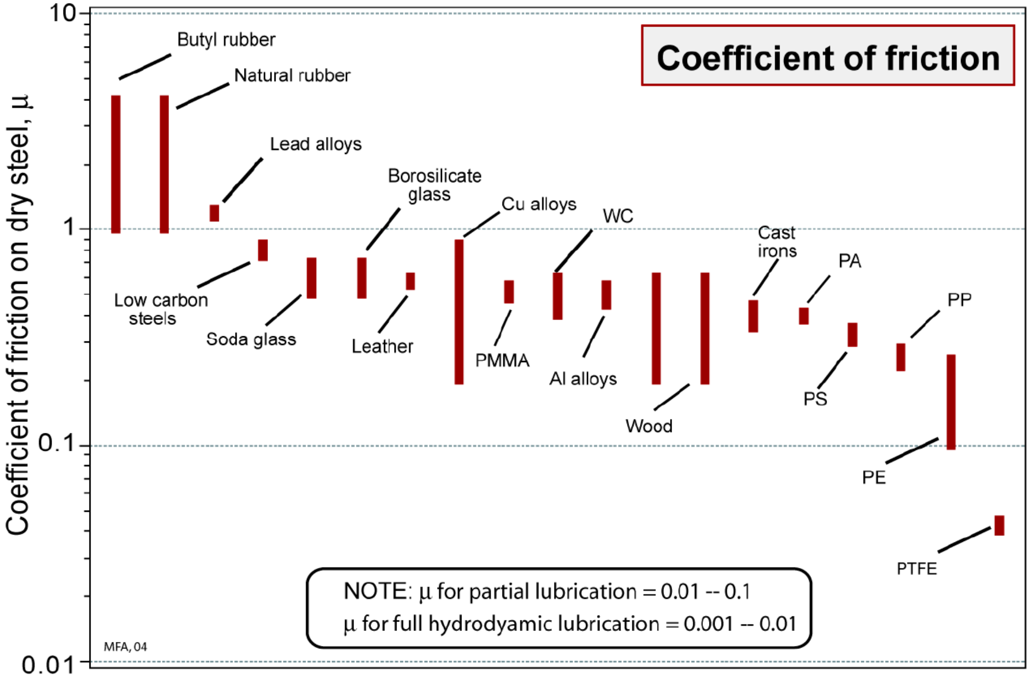


Chart 13: Coefficient of friction

When two surfaces are placed in contact under a normal load F_n and one is made to slide over the other, a force F_s opposes the motion. This force is proportional to F_n but does not depend on the area of the surface – and this is the single most significant result of studies of friction, since it implies that surfaces do not contact completely, but only touch over small patches, the area of which is independent of the apparent, nominal area of contact A_n. The *coefficient friction* μ is defined by

$$\mu = \frac{F_s}{F_n}$$

Approximate values for μ for dry – that is, unlubricated – sliding of materials on a steel couterface are shown here. Typically, $\mu \approx 0.5$. Certain materials show much higher values, either because they seize when rubbed together (a soft metal rubbed on itself with no lubrication, for instance) or because one surface has a sufficiently low modulus that it conforms to the other (rubber on rough concrete). At the other extreme are a sliding combinations with exceptionally low coefficients of friction, such as PTFE, or bronze bearings loaded graphite, sliding on polished steel. Here the coefficient of friction falls as low as 0.04, though this is still high compared with friction for lubricated surfaces, as noted at the bottom of the diagram.



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

Chart 14: Wear rate constant, k_a, against Hardness, H

When surfaces slide, they wear. Material is lost from both surfaces, even when one is much harder than the other. The ***wear-rate***, W, is conventionally defined as

$$W = \frac{Volume\ of\ material\ removed}{Distance\ slid}$$

and thus has units of m^2. A more useful quantity, for our purposes, is the specific wear-rate

$$\Omega = \frac{W}{A_n}$$

which is dimensionless. It increases with bearing pressure P (the normal force F_n divided by the nominal area A_n), such that the ratio

$$k_a = \frac{W}{F_n} = \frac{\Omega}{P}$$

is roughly constant. The quantity k_a (with units of (MPa)$^{-1}$) is a measure of the propensity of a sliding couple for wear: high k_a means rapid wear at a given bearing pressure. Here it is plotted against hardness, H.

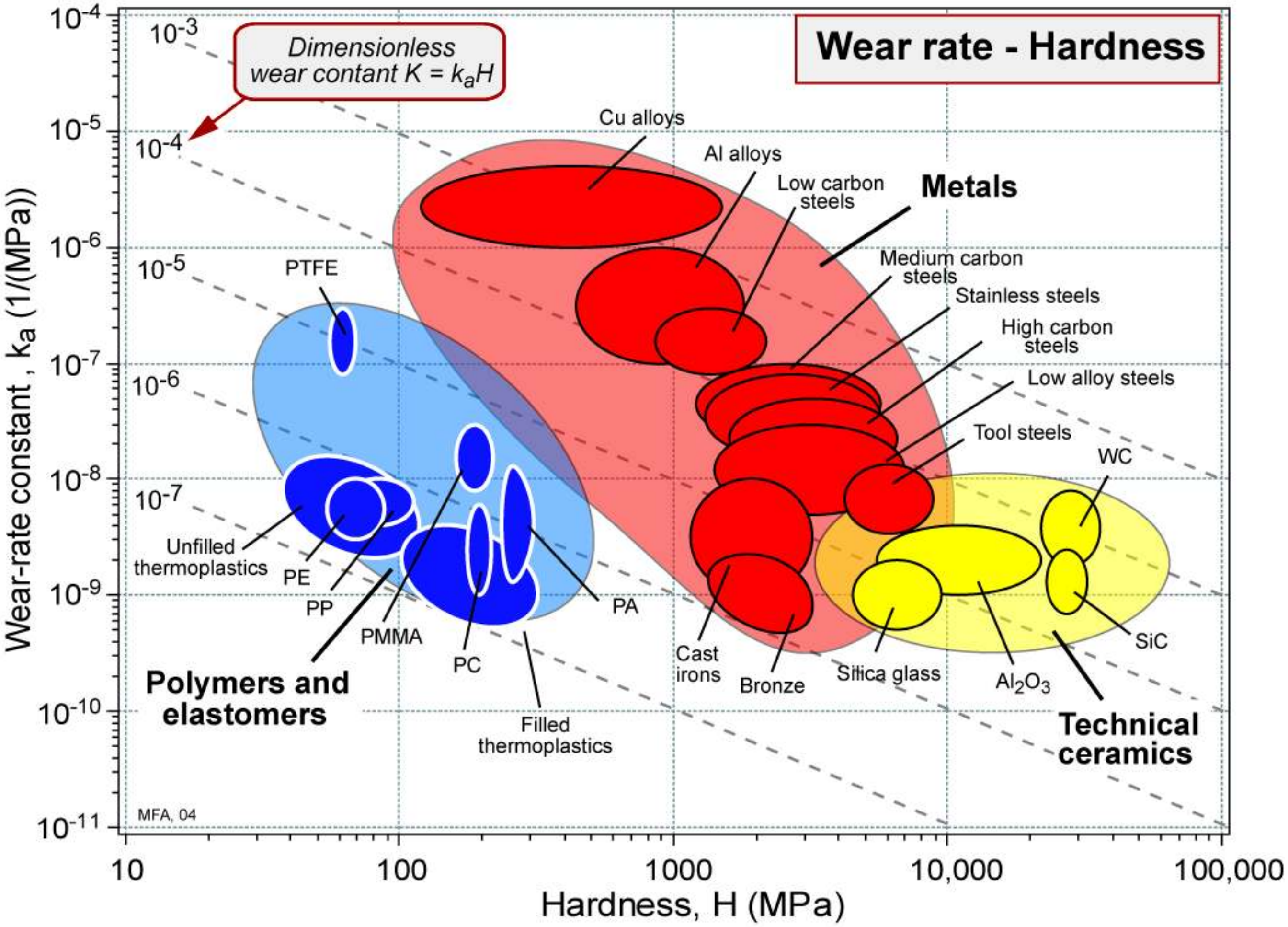
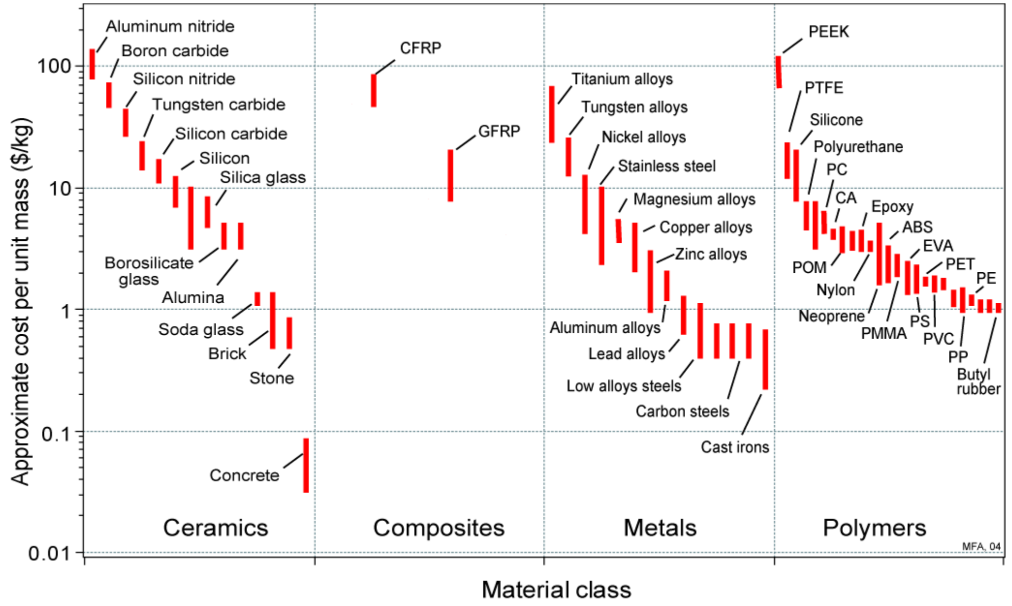


Chart 15 a and b: Approximate material prices, C_m and ρC_m

Properties like modulus, strength or conductivity do not change with time. Cost is bothersome because it does. Supply, scarcity, speculation and inflation contribute to the considerable fluctuations in the cost-per-kilogram of a commodity like copper or silver. Data for cost-per-kg are tabulated for some materials in daily papers and trade journals; those for others are harder to come by. Approximate values for the cost of materials per kg, and their cost per m^3, are plotted in these two charts. Most commodity materials (glass, steel, aluminum, and the common polymers) cost between 0.5 and 2 \$/kg. Because they have low densities, the cost/m^3 of commodity polymers is less than that of metals.



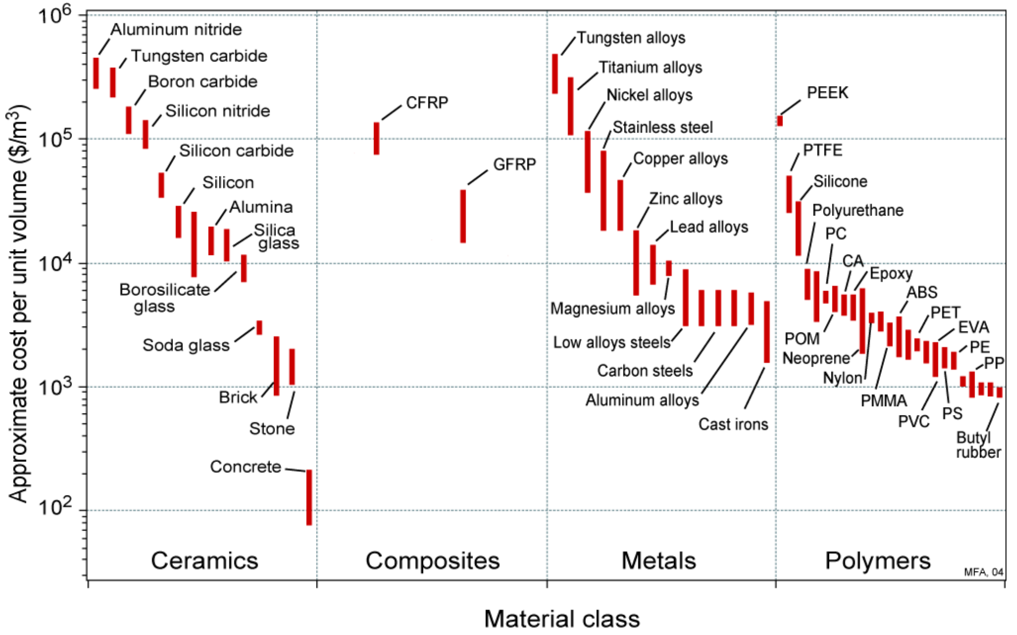


Chart 16: Young's modulus, *E*, against Relative cost, $C_R\rho$

In design for minimum cost, material selection is guided by indices that involve modulus, strength and cost per unit volume. To make some correction for the influence of inflation and the units of currency in which cost is measured, we define a *relative cost per unit volume* $C_{v,R}$

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

At the time of writing, steel reinforcing rod costs about US$ 0.3/kg.

The chart shows the modulus E plotted against relative cost per unit volume $C_{v,R}\,\rho$ where ρ is the density. Cheap stiff materials lie towards the top left. Guide lines for selection materials that are stiff and cheap are plotted on the figure.

The guide lines show the loci of points for which

(a) $E / C_{v,R}\,\rho\ = C$ (minimum cost design of stiff ties, etc)

(b) $E^{1/2} / C_{v,R}\,\rho\ = C$ (minimum cost design of stiff beams and columns)

(c) $E^{1/3} / C_{v,R}\,\rho\ = C$ (minimum cost design of stiff plates)

The value of the constant C increases as the lines are displayed upwards and to the left. Materials offering the greatest stiffness per unit cost lie towards the upper left corner.

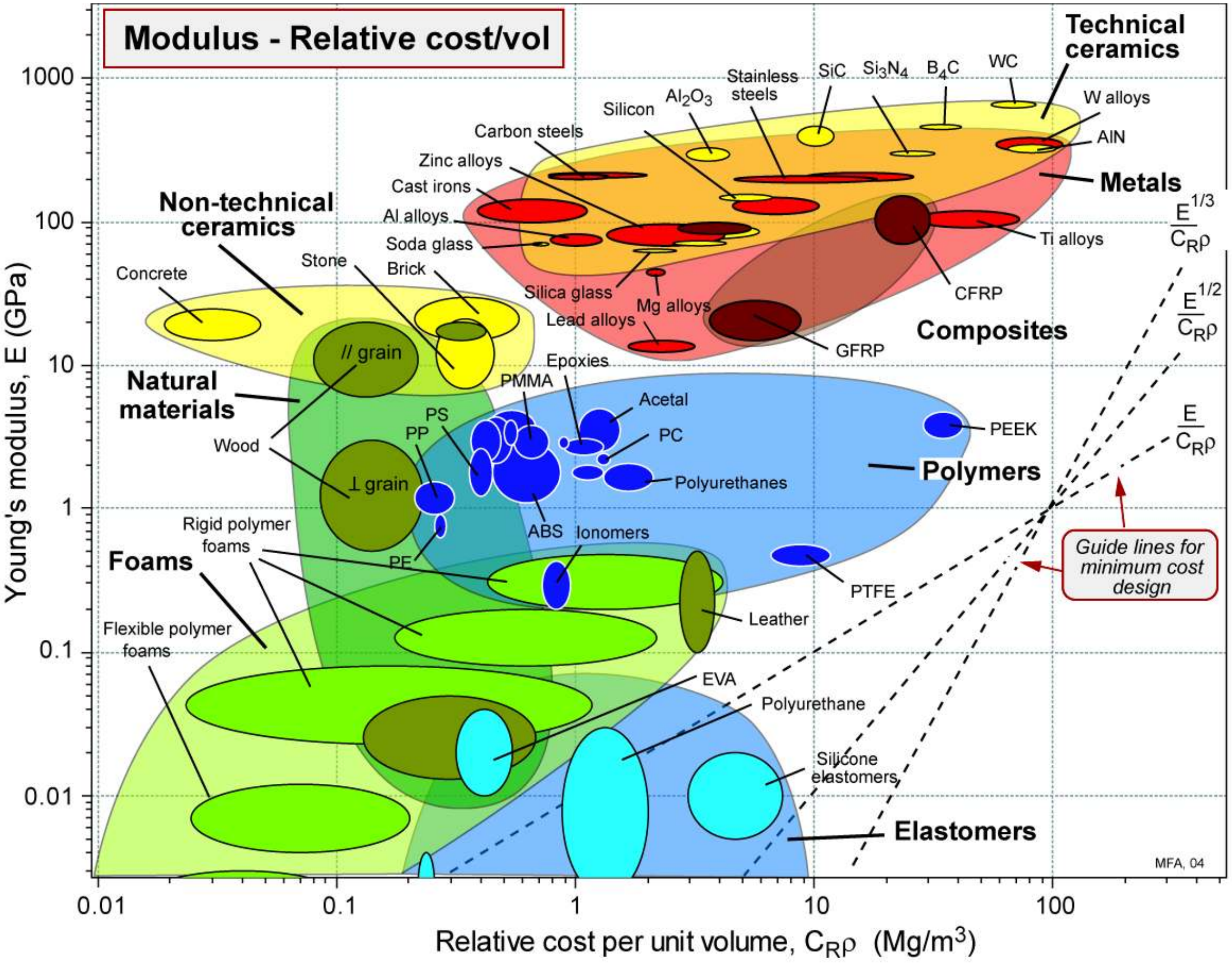


Chart 17: Strength, σ_f, against Relative cost, $C_R\rho$

Cheap strong materials are selected using this chart. It shows strength, defined as before, plotted against relative cost per unit volume, defined on chart 16. The qualifications on the definition of strength, given earlier, apply here also.

It must be emphasised that the data plotted here and on the chart 16 are less reliable than those of other charts, and subject to unpredictable change. Despite this dire warning, the two charts are genuinely useful. They allow selection of materials, using the criterion of "function per unit cost".

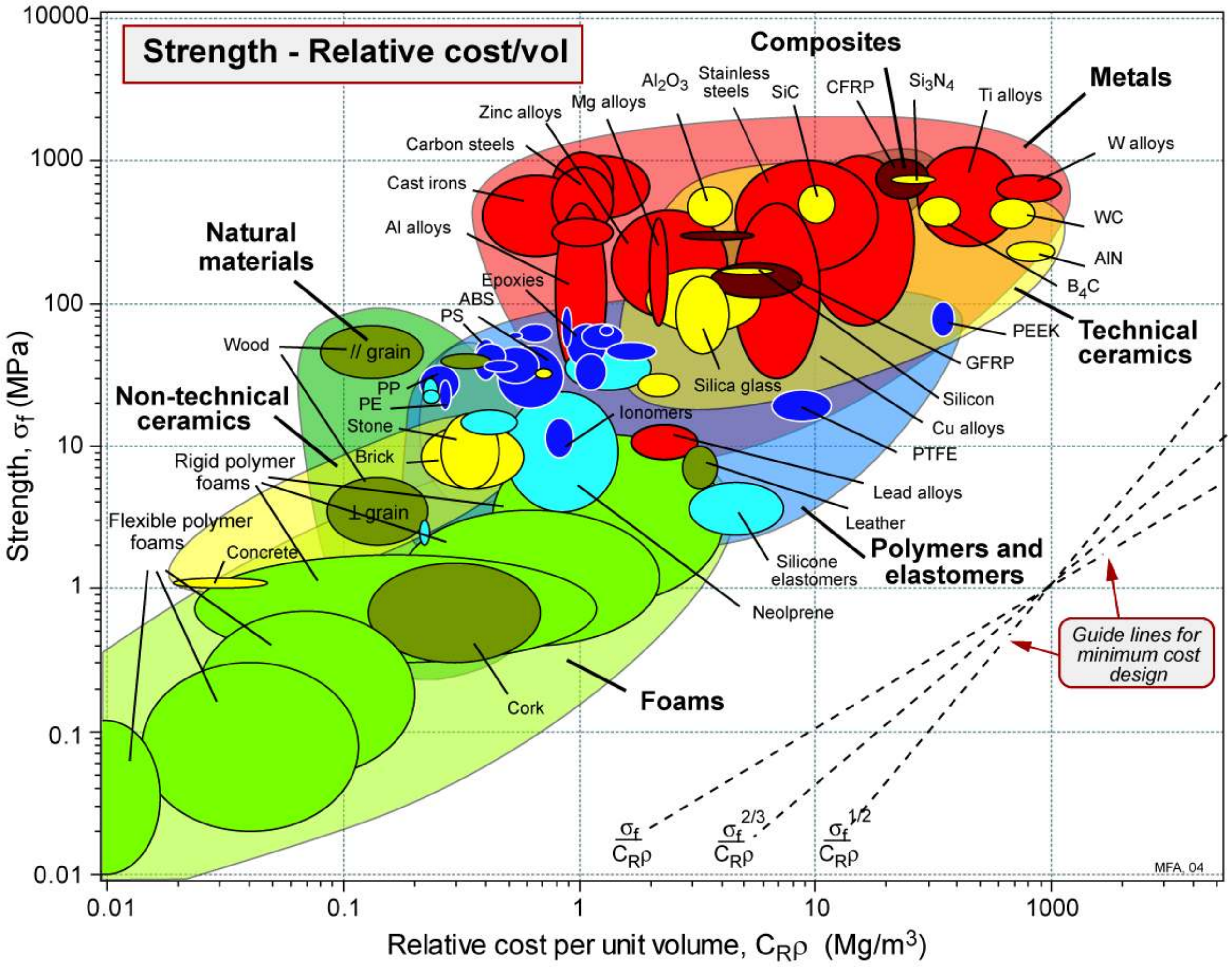
The guide lines show the loci of points for which

(a) $\sigma_f / C_{v,R}\,\rho = C$ (minimum cost design of strong ties, rotating disks, etc)

(b) $\sigma_f^{2/3} / C_{v,R}\,\rho = C$ (minimum cost design of strong beams and shafts)

(c) $\sigma_f^{1/2} / C_{v,R}\,\rho = C$ (minimum cost design of strong plates)

The value of the constants C increase as the lines are displaced upwards and to the left. Materials offering the greatest strength per unit cost lie towards the upper left corner.



Charts 18 a and b: Approximate energy content per unit mass and per unit volume

The energy associated with the production of one kilogram of a material is H_p, that per unit volume is $H_p \rho$ where ρ is the density of the material. These two bar-charts show these quantities for ceramics, metals, polymers and composites. On a "per kg" basis (upper chart) glass, the material of the first container, carries the lowest penalty. Steel is higher. Polymer production carries a much higher burden than does steel. Aluminum and the other light alloys carry the highest penalty of all. But if these same materials are compared on a "per m^3" basis (lower chart) the conclusions change: glass is still the lowest, but now commodity polymers such as PE and PP carry a *lower* burden than steel; the composite GFRP is only a little higher.

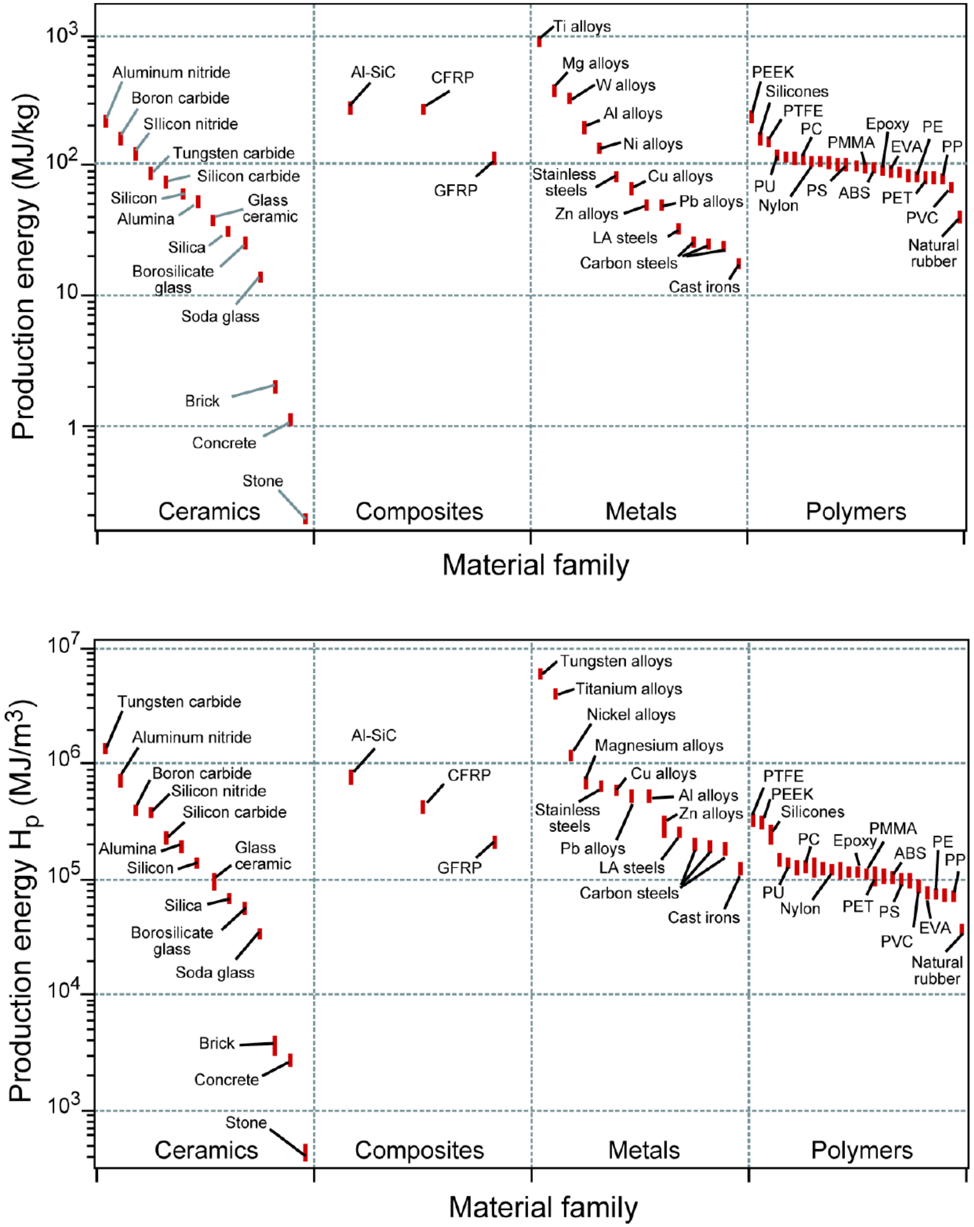


Chart 19: Young's modulus, E, against Energy content, $H_p\rho$

The chart guides selection of materials for stiff, energy-economic components. The energy content per m^3, $H_p\rho$ is the energy content per kg, H_p, multiplied by the density ρ. The guide-lines show the loci of points for which

(a) $E / H_p\rho = C$ (minimum energy design of stiff ties; minimum deflection in centrifugal loading etc)

(b) $E^{1/2} / H_p\rho = C$ (minimum energy design of stiff beams, shafts and columns)

(c) $E^{1/3} / H_p\rho = C$ (minimum energy design of stiff plates)

The value of the constant C increases as the lines are displaced upwards and to the left. Materials offering the greatest stiffness per energy content lie towards the upper left corner.

Other moduli are obtained approximately from E using

- $\nu = 1/3$; $G = 3/8E$; $K \approx E$ (metals, ceramics, glasses and glassy polymers)
- or $\nu \approx 0.5$; $G \approx E/3$; $K \approx 10E$ (elastomers, rubbery polymers)

where ν is Poisson's ratio, G the shear modulus and K the bulk modulus.

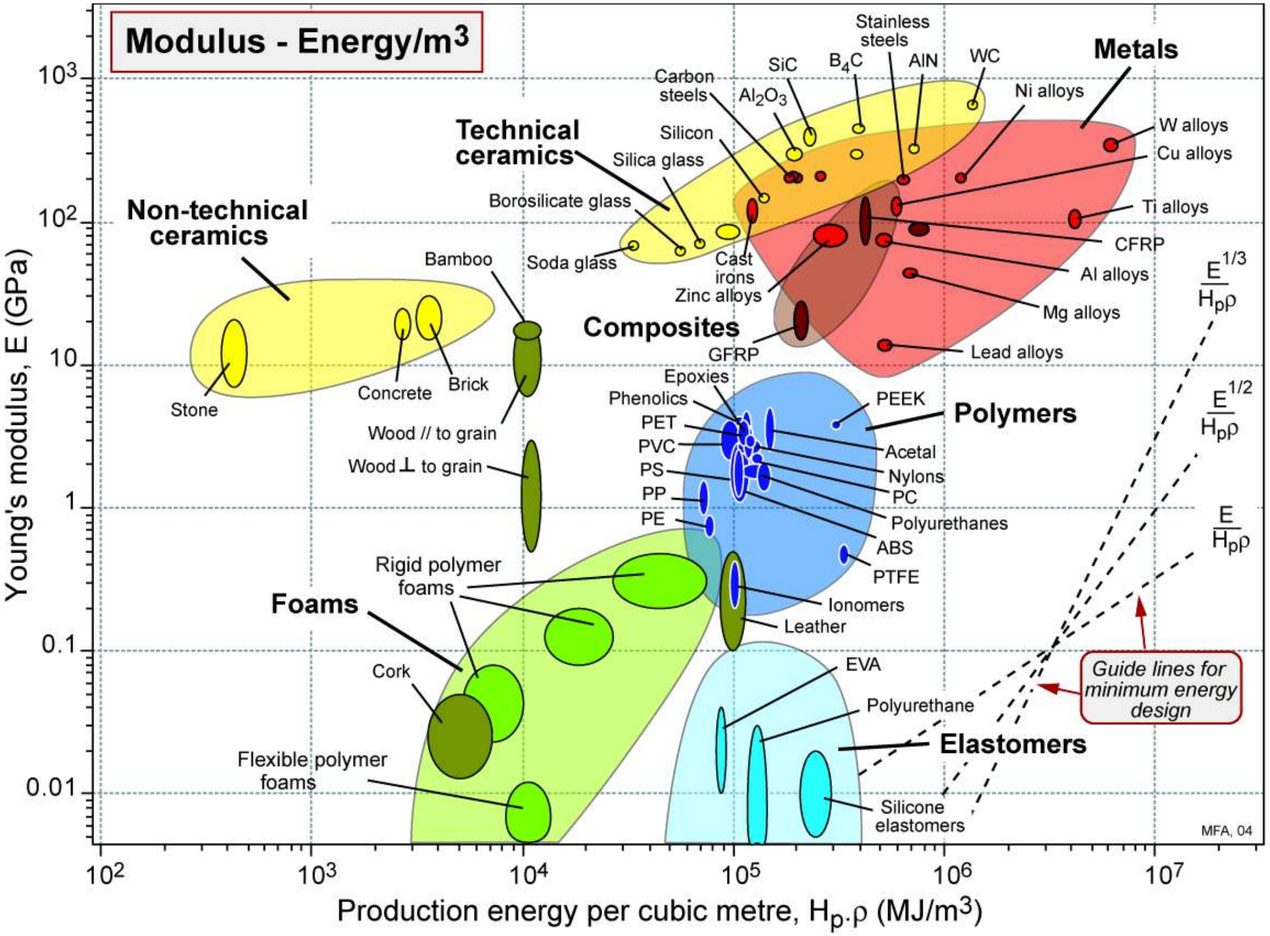


Chart 20: Strength, σ_f, against Energy content, $H_p\rho$

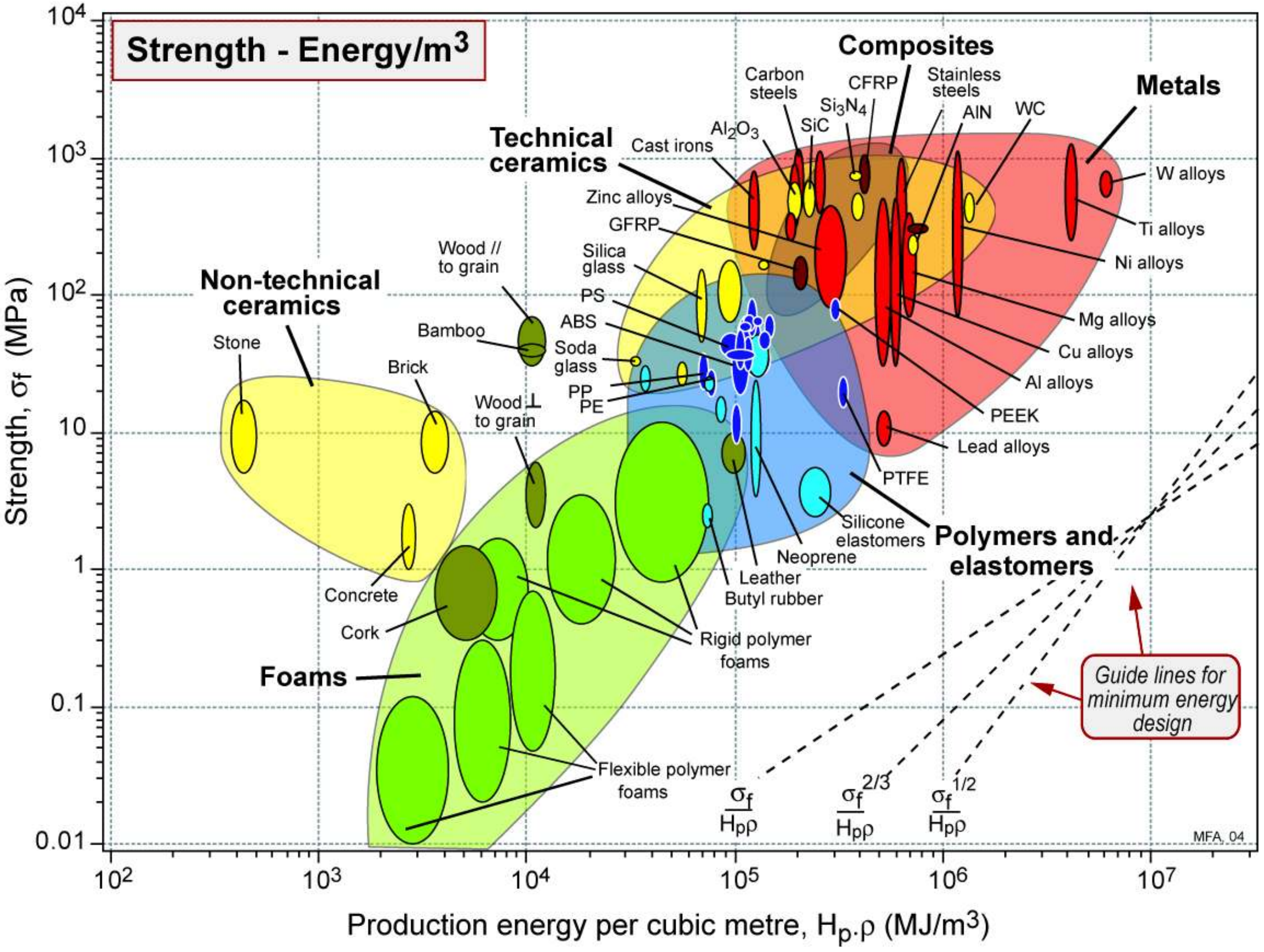
The chart guides selection of materials for strong, energy-economic components. The "strength" for metals is the 0.2% offset yield strength. For polymers, it is the stress at which the stress-strain curve becomes markedly non-linear - typically, a strain of about 1%. For ceramics and glasses, it is the compressive crushing strength; remember that this is roughly 15 times larger than the tensile (fracture) strength. For composites it is the tensile strength. For elastomers it is the tear-strength. The energy content per m^3, $H_p\rho$ is the energy content per kg, H_p, multiplied by the density ρ. The guide lines show the loci of points for which

(a) $\sigma_f / H_p\rho = C$ (minimum energy design of strong ties; maximum rotational velocity of disks)

(b) $\sigma_f^{2/3} / H_p\rho = C$ (minimum energy design of strong beams and shafts)

(c) $\sigma_f^{1/2} / H_p\rho = C$ (minimum energy design of strong plates)

The value of the constant C increases as the lines are displaced upwards and to the left. Materials offering the greatest strength per unit energy content lie towards the upper left corner.



Process attribute charts

Process classes and class members

A *process* is a method of shaping, finishing or joining a material. *Sand casting*, *injection molding*, *fusion welding* and *polishing* are all processes. The choice, for a given component, depends on the material of which it is to be made, on its size, shape and precision, and on how many are required

The manufacturing processes of engineering fall into nine broad classes:

Process classes	
Casting	(sand, gravity, pressure, die, etc)
Pressure molding	(direct, transfer, injection, etc)
Deformation processes	(rolling, forging, drawing, etc)
Powder methods	(slip cast, sinter, hot press, hip)
Special methods	(CVD, electroform, lay up, etc)
Machining	(cut, turn, drill, mill, grind, etc)
Heat treatment	(quench, temper, solution treat, age, etc)
Joining	(bolt, rivet, weld, braze, adhesives)
Surface finish	(polish, plate, anodise, paint)

Each process is characterised by a set of *attributes:* the materials it can handle, the shapes it can make and their precision, complexity and size and so forth. Process Selection Charts map the attributes, showing the ranges of size, shape, material, precision and surface finish of which each class of process is capable. They are used in the way described in "Materials Selection in Mechanical Design". The procedure does not lead to a final choice of process. Instead, it identifies a subset of processes which have the potential to meet the design requirements. More specialised sources must then be consulted to determine which of these is the most economical.

The hard-copy versions, shown here, are necessarily simplified, showing only a limited number of processes and attributes. Computer implementation, as in the CES Edu software, allows exploration of a much larger number of both.

Chart P1 The Process – Material matrix.

A given process can shape, or join, or finish some materials but not others. The matrix shows the links between material and process classes. A red dot indicates that the pair are compatible. Processes that cannot shape the material of choice are non-starters. The upper section of the matrix describes shaping processes. The two sections at the bottom cover joining and finishing.

		Metals, ferrous	Metals, non-ferrous	Ceramics	Glasses	Elastomers	Thermoplastics	Thermosets	Polymer foams	Composites
Shaping	Sand casting	●	●							
	Die casting	●	●							
	Investment casting	●	●							
	Low pressure casting		●							
	Forging	●	●							
	Extrusion		●							
	Sheet forming	●	●							
	Powder methods	●	●	●						
	Electro-machining	●	●	●						
	Conventional machining	●	●	●	●	●	●	●	●	
	Injection molding				●	●	●	●	●	
	Blow molding				●		●			
	Compression molding				●	●	●	●		
	Rotational molding					●	●	●	●	
	Thermo-forming					●	●	●		
	Polymer casting					●	●	●	●	
	Resin-transfer molding						●	●	●	●
	Filament winding									●
	Lay-up methods									●
	Vacuum bag									●
Joining	Adhesives	●	●	●	●	●	●	●	●	●
	Welding, metals	●	●							
	Welding, polymers					●	●	●	●	
	Fasteners	●	●	●	●	●	●	●	●	●
Finishing	Precision machining	●	●				●	●		●
	Grinding	●	●	●	●					●
	Lapping	●	●	●	●					●
	Polishing	●	●	●	●		●	●		●

Chart P2 The Process – Shape matrix.

Shape is the most difficult attribute to characterize. Many processes involve rotation or translation of a tool or of the workpiece, directing our thinking towards axial symmetry, translational symmetry, uniformity of section and such like. *Turning* creates axisymmetric (or circular) shapes; *extrusion, drawing* and *rolling* make prismatic shapes, both circular and non-circular. *Sheet-forming* processes make flat shapes (stamping) or dished shapes (drawing). Certain processes can make 3-dimensional shapes, and among these some can make hollow shapes whereas others cannot.

The process-shape matrix displays the links between the two. If the process cannot make the desired shape, it may be possible to combine it with a secondary process to give a process-chain that adds the additional features: casting followed by machining is an obvious example.

Information about material compatibility is included at the extreme left.

		Circular prismatic	Non-circular prismatic	Flat sheet	Dished sheet	3-D solid	3-D hollow
Metal shaping	Sand casting	●	●			●	●
Metal shaping	Die casting	●	●			●	●
Metal shaping	Investment casting	●	●			●	●
Metal shaping	Low pressure casting	●	●			●	●
Metal shaping	Forging	●	●			●	
Metal shaping	Extrusion	●	●				
Metal shaping	Sheet forming	●	●	●	●		
Metal shaping Ceramic shaping	Powder methods	●	●			●	●
Metal shaping Ceramic shaping	Electro-machining	●	●	●		●	●
Metal shaping Ceramic shaping Polymer shaping	Conventional machining	●	●	●	●	●	●
Ceramic shaping Polymer shaping	Injection molding	●	●			●	●
Polymer shaping	Blow molding				●		●
Polymer shaping	Compression molding			●	●	●	
Polymer shaping	Rotational molding				●		●
Polymer shaping	Thermo-forming				●		
Polymer shaping	Polymer casting	●	●			●	●
Polymer shaping Composite shaping	Resin-transfer molding	●	●	●	●	●	●
Composite shaping	Filament winding	●	●		●		●
Composite shaping	Lay-up methods			●	●	●	
Composite shaping	Vacuum bag			●	●		

Chart P3 The Process – Mass-range chart.

The bar-chart shows the typical mass-range of components that each processes can make. It is one of four, allowing application of constraints on size (measured by mass), section thickness, tolerance and surface roughness. Large components can be built up by joining smaller ones. For this reason the ranges associated with joining are shown in the lower part of the figure. In applying a constraint on mass, we seek single shaping-processes or shaping-joining combinations capable of making it, rejecting those that cannot.

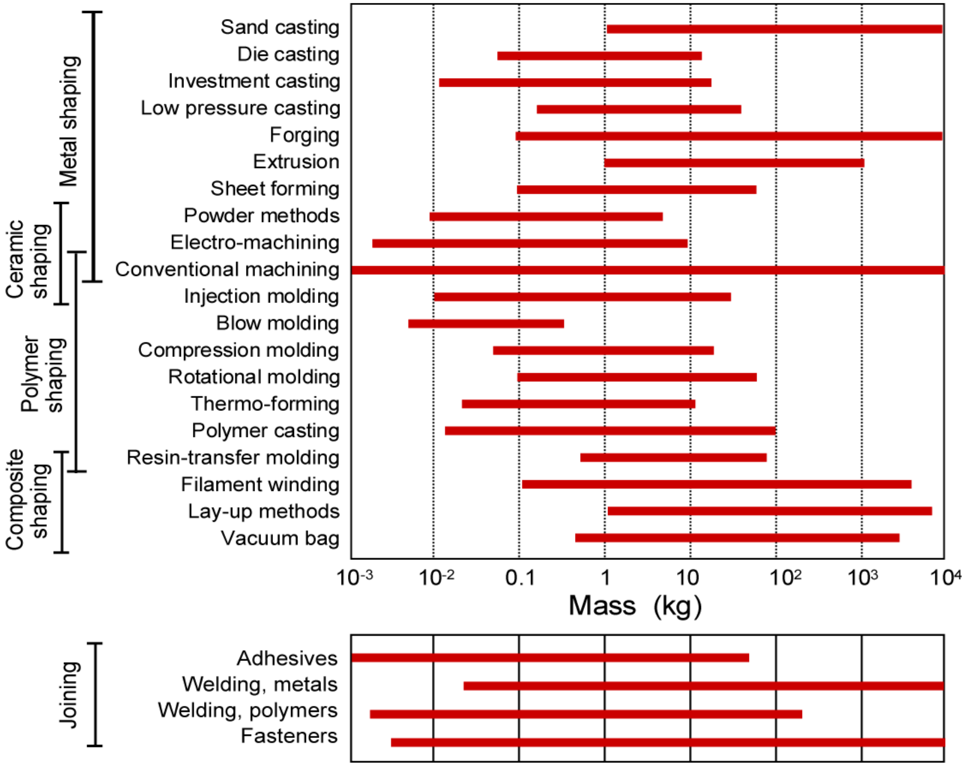


Chart P4 The Process – Section thickness chart.

The bar-chart on the right allows selection to meet constraints on section thickness. Surface tension and heat-flow limit the minimum section of gravity cast shapes. The range can be extended by applying a pressure or by pre-heating the mold, but there remain definite lower limits for the section thickness. Limits on rolling and forging-pressures set a lower limit on thickness achievable by deformation processing. Powder-forming methods are more limited in the section thicknesses they can create, but they can be used for ceramics and very hard metals that cannot be shaped in other ways. The section thicknesses obtained by polymer-forming methods – injection molding, pressing, blow-molding, etc – depend on the viscosity of the polymer; fillers increase viscosity, further limiting the thinness of sections. Special techniques, which include electro-forming, plasma-spraying and various vapour – deposition methods, allow very slender shapes.

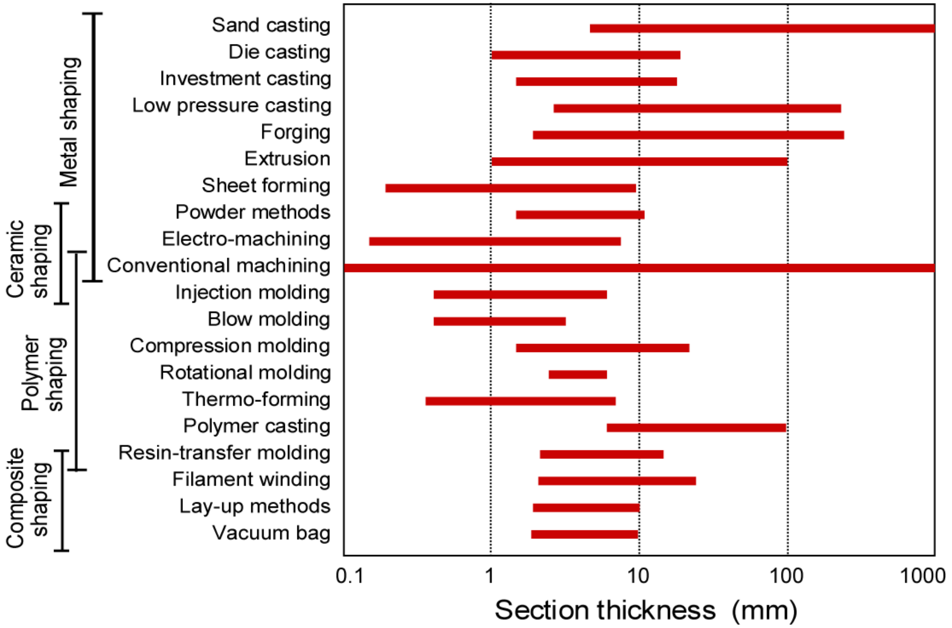


Chart P5 The Process – Tolerance chart.

No process can shape a part *exactly* to a specified dimension. Some deviation Δx from a desired dimension x is permitted; it is referred to as the *tolerance,* T, and is specified as $x = 100 \pm 0.1$ mm, or as $x = 50^{+0.01}_{-0.001}$ mm. This bar chart allows selection to achieve a given tolerance.

The inclusion of finishing processes allows simple process chains to be explored

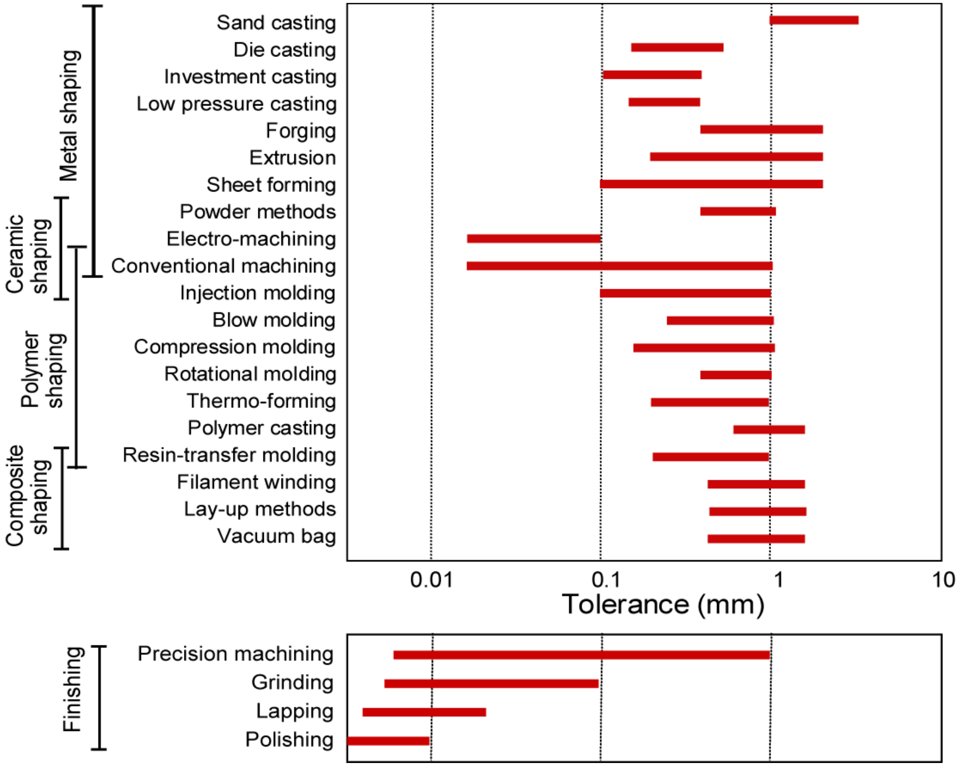


Chart P6 The Process – Surface roughness chart.

The *surface roughness* R, is measured by the root-mean-square amplitude of the irregularities on the surface. It is specified as $R < 100$ µm (the rough surface of a sand casting) or $R < 0.01$ µm (a highly polished surface). The bar chart on the right allows selection to achieve a given surface roughness.

The inclusion of finishing processes allows simple process chains to be explored.

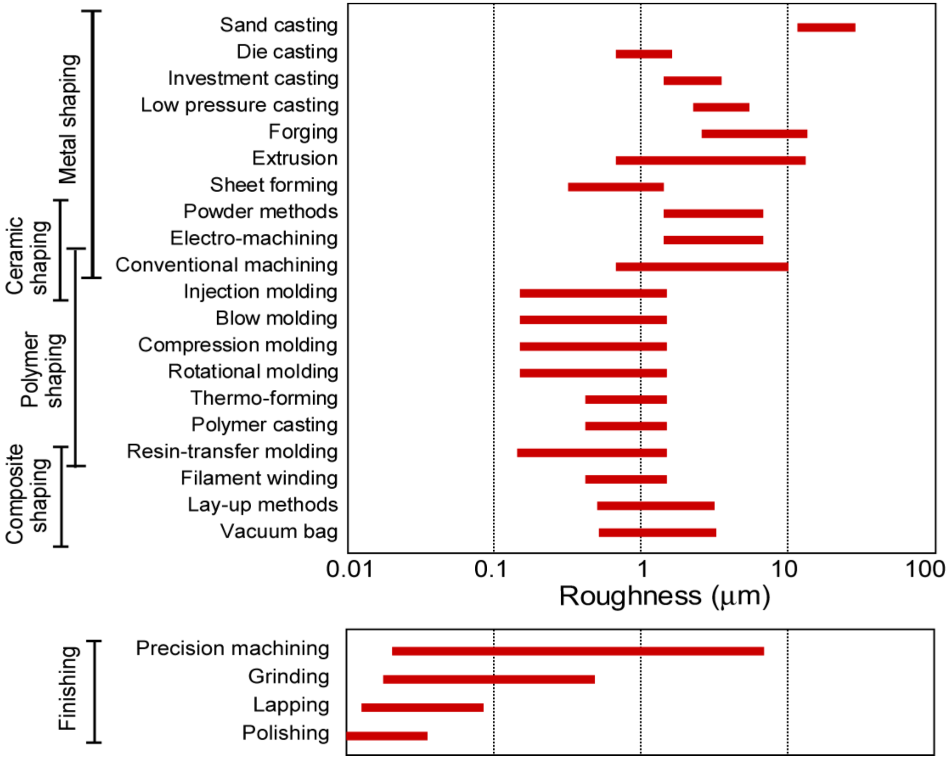
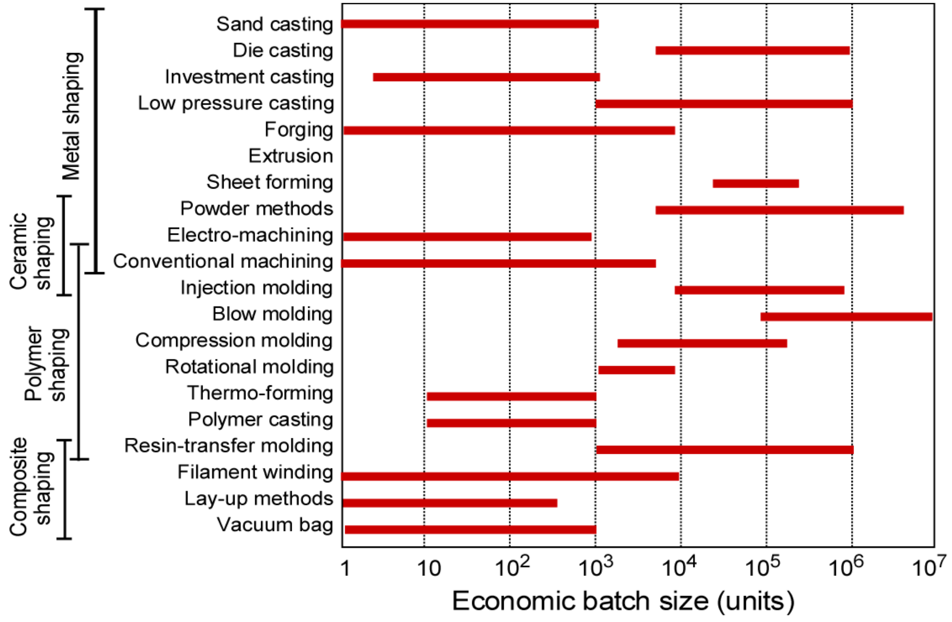


Chart P7 The Process – Economic batch-size chart.

Process cost depends on a large number of independent variables. The influence of many of the inputs to the cost of a process are captured by a single attribute: the *economic batch size*. A process with an economic batch size with the range $B_1 - B_2$ is one that is found by experience to be competitive in cost when the output lies in that range.



Appendix: material indices

Introduction and synopsis

The performance, P, of a component is characterized by a performance equation. The performance equation contains groups of material properties. These groups are the material indices. Sometimes the "group" is a single property; thus if the performance of a beam is measured by its stiffness, the performance equation contains only one property, the elastic modulus E. It is the material index for this problem. More commonly the performance equation contains a group of two or more properties. Familiar examples are the specific stiffness, E/ρ, and the specific strength, σ_y/ρ, (where σ_y is the yield strength or elastic limit, and ρ is the density), but there are many others. They are a key to the optimal selection of materials. Details of the method, with numerous examples are given in Chapters 5 and 6 and in the book “Case studies in materials selection”. This Appendix compiles indices for a range of common applications.

Uses of material indices

Material selection. Components have functions: to carry loads safely, to transmit heat, to store energy, to insulate, and so forth. Each function has an associated material index. Materials with high values of the appropriate index maximize that aspect of the performance of the component. For reasons given in Chapter 5, the material index is generally independent of the details of the design. Thus the indices for beams in the tables that follow are independent of the detailed shape of the beam; that for minimizing thermal distortion of precision instruments is independent of the configuration of the instrument, and so forth. This gives them great generality.

Material deployment or substitution. A new material will have potential application in functions for which its indices have unusually high values. Fruitful applications for a new material can be identified by evaluating its indices and comparing them with those of existing, established materials. Similar reasoning points the way to identifying viable substitutes for an incumbent material in an established application.

How to read the tables. The indices listed in the Tables 1 to 7 are, for the most part, based on the objective of minimizing mass. To minimize cost, use the index for minimum mass, replacing the density ρ by the cost per unit volume, $C_m\rho$, where C_m is the cost per kg. To minimize energy content or CO_2 burden, replace ρ by $H_p\rho$ or by $CO_2\rho$ where H_p is the production energy per kg and CO_2 is the CO_2 burden per kg.

Table A1 Stiffness-limited design at minimum mass (cost, energy, eco-impact)

FUNCTION and CONSTRAINTS	Maximize
TIE (tensile strut) stiffness, length specified; section area free	E/ρ
SHAFT (loaded in torsion) stiffness, length, shape specified, section area free stiffness, length, outer radius specified; wall thickness free stiffness, length, wall-thickness specified; outer radius free	 $G^{1/2}/\rho$ G/ρ $G^{1/3}/\rho$
BEAM (loaded in bending) stiffness, length, shape specified; section area free stiffness, length, height specified; width free stiffness, length, width specified; height free	 $E^{1/2}/\rho$ E/ρ $E^{1/3}/\rho$
COLUMN (compression strut, failure by elastic buckling) buckling load, length, shape specified; section area free	$E^{1/2}/\rho$
PANEL (flat plate, loaded in bending) stiffness, length, width specified, thickness free	$E^{1/3}/\rho$
PLATE (flat plate, compressed in-plane, buckling failure) collapse load, length and width specified, thickness free	$E^{1/3}/\rho$
CYLINDER WITH INTERNAL PRESSURE elastic distortion, pressure and radius specified; wall thickness free	E/ρ
SPHERICAL SHELL WITH INTERNAL PRESSURE elastic distortion, pressure and radius specified, wall thickness free	$E/(1-\nu)\rho$

Table A2 Strength-limited design at minimum mass (cost, energy, eco-impact)

FUNCTION and CONSTRAINTS	Maximize
TIE (tensile strut) stiffness, length specified; section area free	σ_f/ρ
SHAFT (loaded in torsion) load, length, shape specified, section area free load, length, outer radius specified; wall thickness free load, length, wall-thickness specified; outer radius free	 $\sigma_f^{2/3}/\rho$ σ_f/ρ $\sigma_f^{1/2}/\rho$
BEAM (loaded in bending) load, length, shape specified; section area free load length, height specified; width free load, length, width specified; height free	 $\sigma_f^{2/3}/\rho$ σ_f/ρ $\sigma_f^{1/2}/\rho$
COLUMN (compression strut) load, length, shape specified; section area free	σ_f/ρ
PANEL (flat plate, loaded in bending) stiffness, length, width specified, thickness free	$\sigma_f^{1/2}/\rho$
PLATE (flat plate, compressed in-plane, buckling failure) collapse load, length and width specified, thickness free	$\sigma_f^{1/2}/\rho$
CYLINDER WITH INTERNAL PRESSURE elastic distortion, pressure and radius specified; wall thickness free	σ_f/ρ
SPHERICAL SHELL WITH INTERNAL PRESSURE elastic distortion, pressure and radius specified, wall thickness free	σ_f/ρ
FLYWHEELS, ROTATING DISKS maximum energy storage per unit volume; given velocity maximum energy storage per unit mass; no failure	 ρ σ_f/ρ

Table A3 Strength-limited design: springs, hinges etc for maximum performance

FUNCTION and CONSTRAINTS	Maximize
SPRINGS maximum stored elastic energy per unit volume; no failure maximum stored elastic energy per unit mass; no failure	 σ_f^2 / E $\sigma_f^2 / E \rho$
ELASTIC HINGES radius of bend to be minimized (max flexibility without failure)	σ_f / E
KNIFE EDGES, PIVOTS minimum contact area, maximum bearing load	σ_f^3 / E^2 and H
COMPRESSION SEALS AND GASKETS maximum conformability; limit on contact pressure	$\sigma_f^{3/2} / E$ and $1/E$
DIAPHRAGMS maximum deflection under specified pressure or force	$\sigma_f^{3/2} / E$
ROTATING DRUMS AND CENTRIFUGES maximum angular velocity; radius fixed; wall thickness free	σ_f / ρ

Table A4 Vibration-limited design

FUNCTION and CONSTRAINTS	Maximize
TIES, COLUMNS maximum longitudinal vibration frequencies	E / ρ
BEAMS, all dimensions prescribed maximum flexural vibration frequencies **BEAMS, length and stiffness prescribed** maximum flexural vibration frequencies	 E / ρ $E^{1/2} / \rho$
PANELS, all dimensions prescribed maximum flexural vibration frequencies **PANELS, length, width and stiffness prescribed** maximum flexural vibration frequencies	 E / ρ $E^{1/3} / \rho$
TIES, COLUMNS, BEAMS, PANELS, stiffness prescribed minimum longitudinal excitation from external drivers, ties minimum flexural excitation from external drivers, beams minimum flexural excitation from external drivers, panels	 $\eta E / \rho$ $\eta E^{1/2} / \rho$ $\eta E^{1/3} / \rho$

Table A5 Damage-tolerant design

FUNCTION and CONSTRAINTS	Maximize
TIES (tensile member) maximum flaw tolerance and strength, load-controlled design maximum flaw tolerance and strength, displacement-control maximum flaw tolerance and strength, energy-control	K_{Ic} and σ_f K_{Ic}/E and σ_f K_{Ic}^2/E and σ_f
SHAFTS (loaded in torsion) maximum flaw tolerance and strength, load-controlled design maximum flaw tolerance and strength, displacement-control maximum flaw tolerance and strength, energy-control	K_{Ic} and σ_f K_{Ic}/E and σ_f K_{Ic}^2/E and σ_f
BEAMS (loaded in bending) maximum flaw tolerance and strength, load-controlled design maximum flaw tolerance and strength, displacement-control maximum flaw tolerance and strength, energy-control	K_{Ic} and σ_f K_{Ic}/E and σ_f K_{Ic}^2/E and σ_f
PRESSURE VESSEL yield-before-break leak-before-break	K_{Ic}/σ_f K_{Ic}^2/σ_f

Table A6 Thermal and thermo-mechanical design

FUNCTION and CONSTRAINTS	Maximize
THERMAL INSULATION MATERIALS minimum heat flux at steady state; thickness specified minimum temp rise in specified time; thickness specified minimize total energy consumed in thermal cycle (kilns, etc)	$1/\lambda$ $1/a = \rho C_p/\lambda$ $\sqrt{a}/\lambda = \sqrt{1/\lambda \rho C_p}$
THERMAL STORAGE MATERIALS maximum energy stored / unit material cost (storage heaters) maximize energy stored for given temperature rise and time	C_p/C_m $\lambda/\sqrt{a} = \sqrt{\lambda \rho C_p}$
PRECISION DEVICES minimize thermal distortion for given heat flux	λ/a
THERMAL SHOCK RESISTANCE maximum change in surface temperature; no failure	$\sigma_f/E\alpha$
HEAT SINKS maximum heat flux per unit volume; expansion limited maximum heat flux per unit mass; expansion limited	$\lambda/\Delta\alpha$ $\lambda/\rho\Delta\alpha$
HEAT EXCHANGERS (pressure-limited) maximum heat flux per unit area; no failure under Δp maximum heat flux per unit mass; no failure under Δp	$\lambda\sigma_f$ $\lambda\sigma_f/\rho$

Table A7 Electro-mechanical design

FUNCTION and CONSTRAINTS	Maximize
BUS BARS	
minimum life-cost; high current conductor	$1/\rho_e \rho C_m$
ELECTRO-MAGNET WINDINGS	
maximum short-pulse field; no mechanical failure	σ_f
maximize field and pulse-length, limit on temperature rise	$C_p \rho / \rho_e$
WINDINGS, HIGH-SPEED ELECTRIC MOTORS	
maximum rotational speed; no fatigue failure	σ_e / ρ_e
minimum ohmic losses; no fatigue failure	$1/\rho_e$
RELAY ARMS	
minimum response time; no fatigue failure	$\sigma_e / E \rho_e$
minimum ohmic losses; no fatigue failure	$\sigma_e^2 / E \rho_e$

Physical constants and conversion of units

Absolute zero temperature	-273.2^{o}C
Acceleration due to gravity, g	9.807m/s^{2}
Avogadro's number, N_A	6.022 x 10^{23}
Base of natural logarithms, e	2.718
Boltsmann's constant, k	1.381 x 10^{-23} J/K
Faraday's constant k	9.648 x 10^{4} C/mol
Gas constant, $\overline{R}$	8.314 J/mol/K
Planck's constant, h	6.626 x 10^{-34} J/s
Velocity of light in vacuum, c	2.998 x 10^{8} m/s
Volume of perfect gas at STP	22.41 x 10^{-3} m^{3}/mol

Angle, θ	1 rad	57.30^{o}
Density, ρ	1 lb/ft^{3}	16.03 kg/m^{3}
Diffusion Coefficient, D	1cm^{3}/s	1.0 x 10^{-4}m^{2}/s
Energy, U	See opposite	
Force, F	1 kgf 1 lbf 1 dyne	9.807 N 4.448 N 1.0 x 10^{-5}N
Length, ℓ	1 ft 1 inch 1 Å	304.8 mm 25.40 mm 0.1 nm
Mass, M	1 tonne 1 short ton 1 long ton 1 lb mass	1000 kg 908 kg 1107 kg 0.454 kg
Power, P	See opposite	
Stress, σ	See opposite	
Specific Heat, Cp	1 cal/gal.^{o}C Btu/lb.^{o}F	4.188 kJ/kg.^{o}C 4.187 kg/kg.^{o}C
Stress Intensity, K_{1c}	1 ksi √in	1.10 MN/m$^{3/2}$
Surface Energy γ	1 erg/cm^{2}	1 mJ/m^{2}
Temperature, T	1^{o}F	0.556^{o}K
Thermal Conductivity λ	1 cal/s.cm.^{o}C 1 Btu/h.ft.^{o}F	418.8 W/m.^{o}C 1.731 W/m.^{o}C
Volume, V	1 Imperial gall 1 US gall	4.546 x 10^{-3}m^{3} 3.785 x 10^{-3}m^{3}
Viscosity, η	1 poise 1 lb ft.s	0.1 N.s/m^{2} 0.1517 N.s/m^{2}

Conversion of units – stress and pressure*

	MPa	**dyn/cm^{2}**	**lb.in^{2}**	**kgf/mm^{2}**	**bar**	**long ton/in^{2}**
MPa	1	10^{7}	1.45 x 10^{2}	0.102	10	6.48 x 10^{-2}
dyn/cm^{2}	10^{-7}	1	1.45 x 10^{-5}	1.02 x 10^{-8}	10^{-6}	6.48 x 10^{-9}
lb/in^{2}	6.89 x 10^{-3}	6.89 x 10^{4}	1	703 x $^{10-4}$	6.89 x 10^{-2}	4.46 x 10^{-4}
kgf/mm^{2}	9.81	9.81 x 10^{7}	1.42 x 10^{3}	1	98.1	63.5 x 10^{-2}
bar	0.10	10^{6}	14.48	1.02 x 10^{-2}	1	6.48 x 10^{-3}
long ton/ in^{2}	15.44	1.54 x 10^{8}	2.24 x 10^{3}	1.54	1.54 x 10^{2}	1

Conversion of units – energy*

	J	**erg**	**cal**	**eV**	**Btu**	**ft lbf**
J	1	10^{7}	0.239	6.24 x 10^{18}	9.48 x 10^{-4}	0.738
erg	10^{-7}	1	2.39 x 10^{-8}	6.24 x 10^{11}	9.48 x 10^{-11}	7.38 x 10^{-8}
cal	4.19	4.19 x 10^{7}	1	2.61 x 10^{19}	3.97 x 10^{-3}	3.09
eV	1.60 x 10^{-19}	1.60 x 10^{-12}	3.38 x 10^{-20}	1	1.52 x 10^{-22}	1.18 x 10^{-19}
Btu	1.06 x 10^{3}	1.06 x 10^{10}	2.52 x 10^{2}	6.59 x 10^{21}	1	7.78 x 10^{2}
ft lbf	1.36	1.36 x 10^{7}	0.324	8.46 x 10^{18}	1.29 x 10^{-3}	1

Conversion of units – power*

	kW (kJ/s)	**erg/s**	**hp**	**ft lbf/s**
kW (kJ/s)	1	10^{-10}	1.34	7.38 x 10^{2}
erg/s	10^{-10}	1	1.34 x 10^{-10}	7.38 x 10^{-8}
hp	7.46 x 10^{-1}	7.46 x 10^{9}	1	15.50 X 10^{2}
Ft lbf/s	1.36 X 10^{-3}	1.36 X 10^{7}	1.82 X 10^{-3}	1

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The resources come in various formats and are aimed at different levels of student.

This resource is part of a set of resources created by Professor Mike Ashby to help introduce materials and materials selection to students.

The website also contains other resources donated by faculty at the 700+ universities and colleges worldwide using Granta's CES EduPack.

The teaching resource website contains both resources that require the use of CES EduPack and those that don't.

www.grantadesign.com/education/resources