

Module 5 Material Selection

Subject: Material Science and Engineering

Subject Code: 21ME33

Syllabus

The need for material selection in design, the evolution of Engineering materials.

The Design Process and Materials Data: Types of design, design tools and materials data, processes of obtaining materials data, materials databases

Engineering Materials and Their Properties: The classes of engineering materials and their structure, material properties: mechanical properties, functional properties.

Material Selection Charts: Selection criteria for materials, material property Charts, deriving property limits and material indices, materials indices which include shape

The need for material selection 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. The number of materials available to engineers is vast: 160,000 or more. There is the rapid evolution of materials information. A systematic procedure— one with steps that can be taught quickly, that is robust in the decisions it reaches, that allows computer implementation, and that is compatible with the other established tools of engineering design.

The choice of material cannot be made independently of the choice of process by which the material is to be shaped, joined, and finished. Cost enters the equation, both in the choice of material and in the way the material is processed. good engineering design alone is not enough to sell products. In almost everything from home appliances to automobiles and aircraft, the form, texture, feel, color, beauty, and meaning of the product—the satisfaction it gives the person who owns or uses it—are important. This aspect, known confusingly as industrial design, is one that, if neglected, can lose markets. **Good design works; excellent design also gives pleasure.** Design problems are almost always open-ended. They do not have a unique or “correct” solution, though some solutions will clearly be better than others.

The ideas of material and process attributes must be integrated together. To do this they are mapped on material and process selection charts that show the lay of the land. An initial survey for potential candidate materials. trade-off methods are employed where conflicting objectives—minimizing mass while at the same time minimizing cost will have to be considered. The interaction between material and shape can be built into the method. Taken together, these suggest schemes for expanding the boundaries of material performance by creating hybrids—combinations of two or more materials, shapes, and configurations with unique property profiles. None of this can be implemented without data for material properties and process attributes.

Tools such as the CES Edu materials selection platform which is a tool for interfacing with tools for computer-aided design, finite element analysis, optimization routines, and product data management software may be used to make the right choice.

The evolution of Engineering materials

The evolution of materials are illustrated in more detail, in Figure 1.

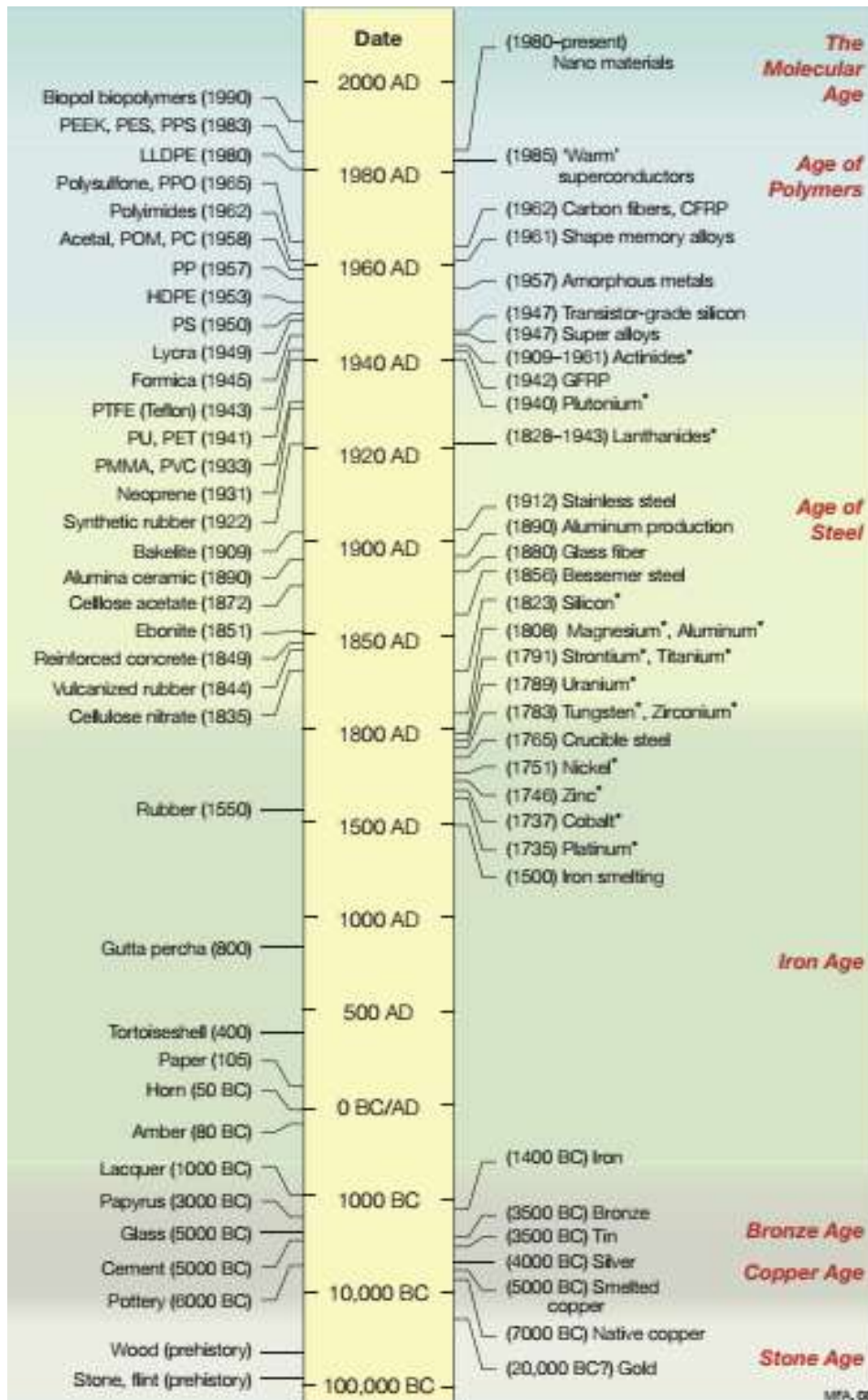
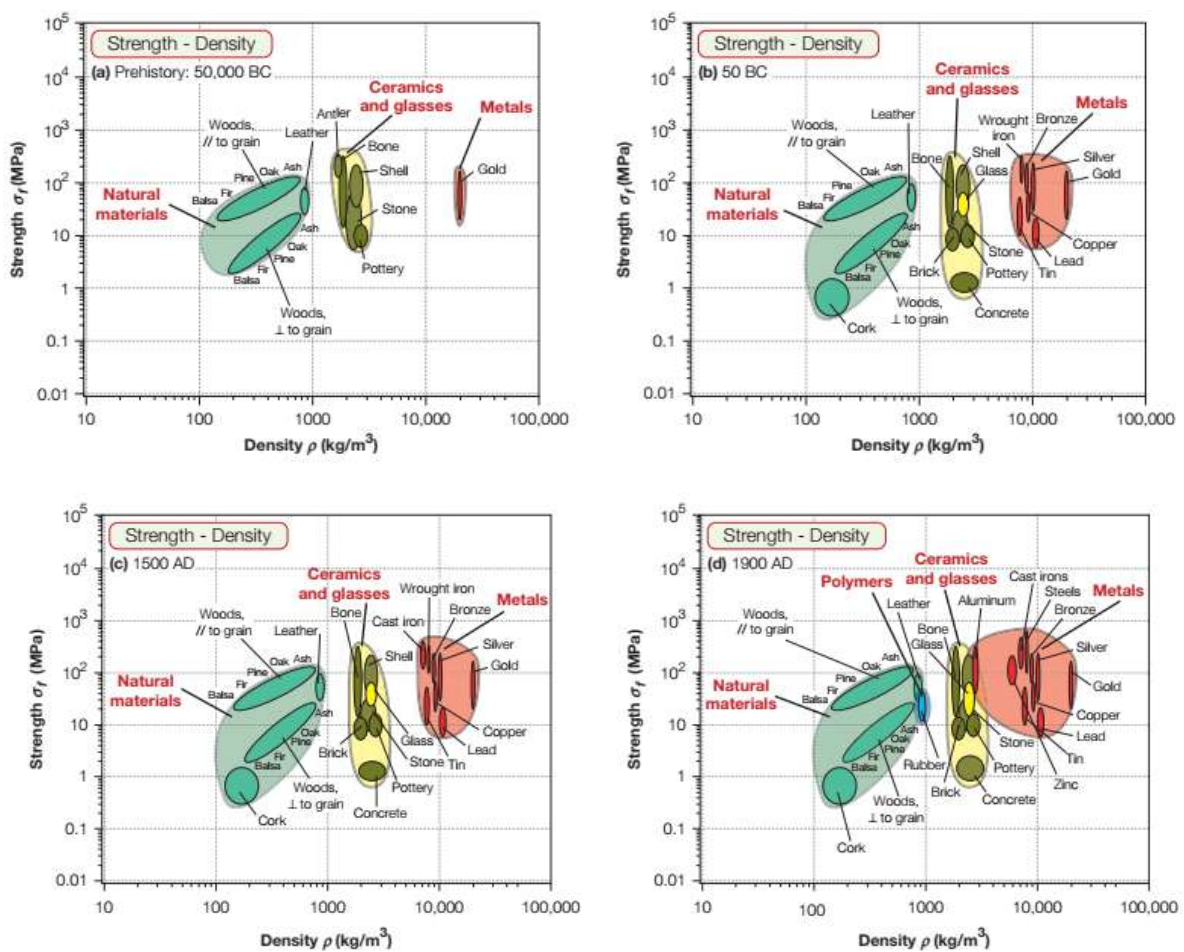


Figure 1: A materials timeline. The scale is nonlinear, with big steps at the bottom, small ones at the top. An asterisk (*) indicates the date at which an element was first identified. Labels without asterisks note the time at which the material became of practical importance.

The materials of prehistory (before 10,000 BC, the Stone Age) were ceramics and glasses, natural polymers, and composites. Weapons—always the peak of technology—were made of wood and flint; buildings and bridges of stone and wood. Naturally occurring gold and silver were available locally and, through their rarity, assumed great influence as currency, but their role in technology was small. The development of rudimentary thermo-chemistry allowed the extraction of, first, copper and bronze, then iron (the Bronze Age, 4000–1000 BC and the Iron Age, 1000 BC–1620 AD), stimulating enormous advances in technology.² Cast iron technology (1620s) established the dominance of metals in engineering; since then the evolution of steels (1850 onward), light alloys (1940s), and special alloys has consolidated their position. By the 1950s, “engineering materials” meant “metals.” Engineers were given courses in metallurgy; other materials were barely mentioned.

There had, been developments in the other classes of material. Improved cements, refractories, and glasses; and rubber, Bakelite, and polyethylene among polymers; but their share of the total materials market was small. Since 1950 all that has changed. The rate of development of new metallic alloys is now slow; demand for steel and cast iron has in some countries actually fallen.

The progression in properties evolved is visualised with the help of material-property charts. Figure 2 shows one of them—a strength-density chart. The oval bubbles plot the range of strength and density of materials; the larger colored envelopes enclose families. The chart is plotted for six successive points in historical time. The materials of pre-history, shown in (a), cover only a tiny fraction of this strength-density



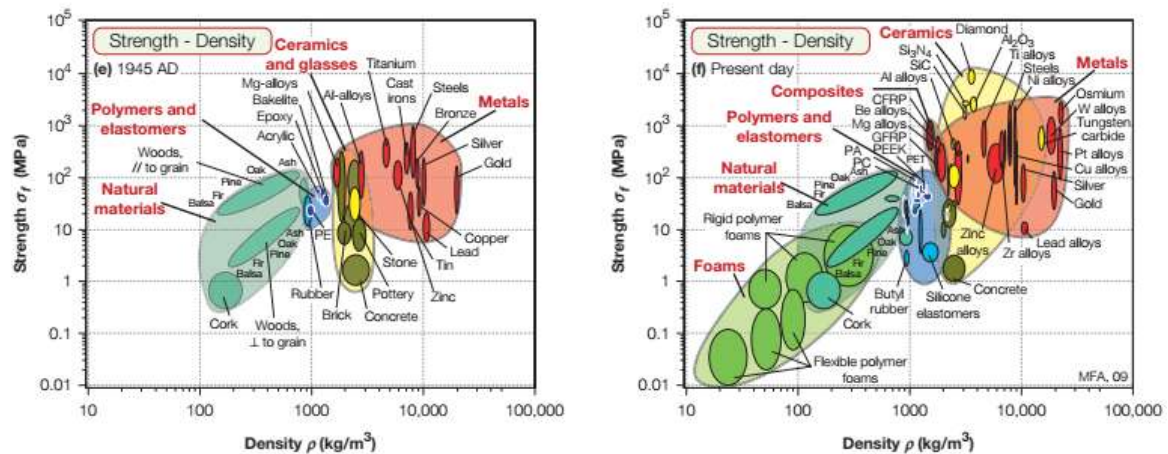


Figure 2: The progressive filling of material-property space over time (the charts list the date at the top left) showing the way the materials have been developed over time to meet demands on strength and density. Similar time plots show the progressive filling for all material properties

space. By the time of the peak of the Roman Empire, around 50 BC (b), the area occupied by metals had expanded considerably, giving Rome critical advantages in weaponry and defence. The progress thereafter was slow: 1500 years later (c) not much has changed, although, significantly, cast iron started to appear. Even 500 years after that (d), expansion of the occupied area of the chart is small; aluminum only just starts to creep in. Then things accelerate. By 1945 the metals envelope has expanded considerably and a new envelope—that of synthetic polymers—occupies a significant position. Between then and the present day the expansion has been dramatic. The filled area now starts to approach some fundamental limits (not shown here) beyond which it is difficult to go.

The Design Process and Materials Data:

Types of design

Original design: it involves a new idea or working principle (the ballpoint pen, the compact disc). New materials can offer new, unique combinations of properties that enable original design. Thus high-purity silicon enabled the transistor; high-purity glass, the optical fiber; high coercive-force magnets, the miniature earphone; solid-state lasers the compact disc. Sometimes the new material suggests the new product. Sometimes, instead, the new product demands the development of a new material: Nuclear technology drove the development of a series of new zirconium alloys and low-carbon stainless steels; space technology stimulated the development of light weight composites; gas turbine technology today drives development of high-temperature alloys and ceramic coatings.

Adaptive or developmental: The starting point is an existing product or product range. The motive for redesigning it may be to enhance performance, to reduce cost, or to adapt it to changing market conditions. Adaptive design takes an existing concept and seeks an incremental advance in performance through a refinement of the working principle. It, too, is

often made possible by developments in materials. Ex: polymers replacing metals in household appliances; carbon fiber replacing wood in sports equipment.

Variant design involves a change of scale or dimension or detailing without a change of function or the method of achieving it: the scaling up of boilers, or of pressure vessels, or of turbines, for instance. Change of scale or circumstances of use may require change of material: Small boats are made of fiberglass, large ships are made of steel; small boilers are made of copper, large ones of steel; subsonic planes are made of one alloy, supersonic of another

Design tools and materials data

The design flow chart. The design proceeds from the identification of a market need, clarified as a set of design requirements, through concept, embodiment, and detailed analysis to a product specification. To implement this use is made of design tools.

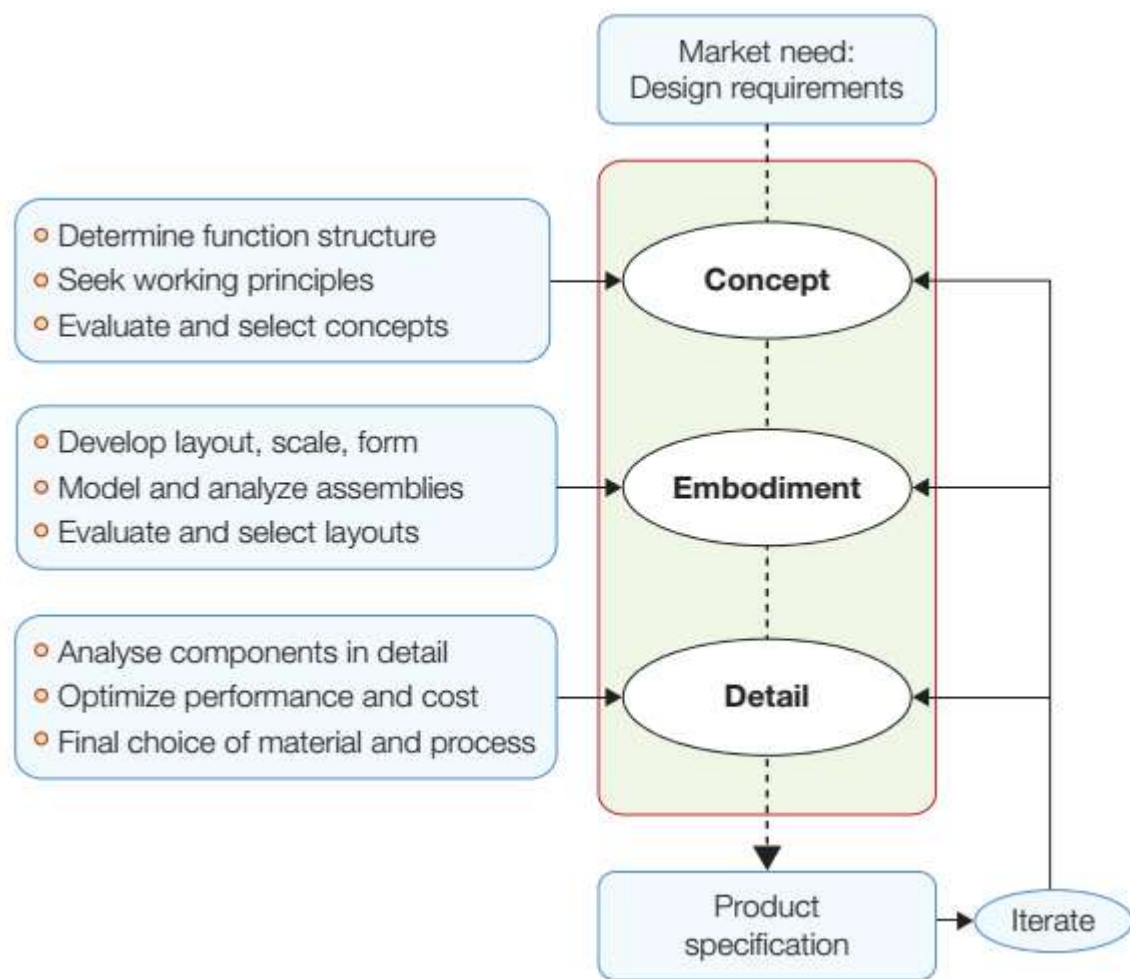


Figure 3: Typical design flow chart

They are shown as inputs, attached to the left of the main backbone of the design methodology in Figure below. The tools enable the modeling and optimization of a design, easing the routine aspects of each phase. Function modelers suggest viable function structures. Configuration optimizers suggest or refine shapes. Geometric and 3D solid modeling packages allow visualization and create files that can be downloaded to numerically controlled prototyping and manufacturing systems. Optimization, DFM, DFA, and cost estimation software allows

manufacturing aspects to be refined. Finite element (FE) and computational fluid dynamics (CFD) packages allow precise mechanical and thermal analysis even when the geometry is complex, deformations are large, and temperatures fluctuate. There is a natural progression in the use of the tools as the design evolves: approximate analysis and modeling at the conceptual stage; more sophisticated modeling and optimization at the embodiment stage; and precise (“exact”—but nothing is ever that) analysis at the detailed design stage.

Tools for material selection play a major part in each stage of the design. The nature of the data needed in the early stages differs greatly in its level of precision and breadth from that needed later on. At the concept stage, the designer requires approximate property values, but for the widest possible range of materials. All options are open: A polymer may be the best choice for one concept, a metal for another, even though the function is the same. The problem, at this stage, is not precision and detail; it is breadth and speed of access.

At the embodiment stage the landscape has narrowed. Here we need data for a subset of materials, but at a higher level of precision and detail. These are found in more specialized handbooks and software that deal with a single class or subclass of materials—metals or just aluminum alloys, for instance. The risk now is that of losing sight of the bigger spread of materials to which we must return if the details don’t work out; it is easy to get trapped in a single line of thinking

The final stage, that of detailed design, requires a still higher level of precision and detail, but for only one or a very few materials. Such information is best found in the datasheets issued by the material producers themselves and in detailed databases for restricted material classes. A given material (polyethylene, for instance) has a range of properties that derive from differences in the ways different producers make it. At the detailed design stage, a supplier must be identified, and the properties of their product used in the design calculations; a product from another supplier may differ. And sometimes even this is not good enough. If the component is a critical one (meaning that its failure could, in some sense or another, be disastrous), then it is prudent to conduct in-house tests to measure the critical properties, using a sample of the material that will be used to make the product itself.

The materials input does not end with the establishment of production. Products fail in service, and failures contain information. It is an imprudent manufacturer who does not collect and analyze data on failures. Often this points to the misuse of a material, one that redesign or reselection can eliminate.

Process of obtaining materials data

The engineer, in selecting materials for a developing design, needs data for the materials’ properties. Engineers are often conservative in their choice, reluctant to consider materials with which they are unfamiliar, and with good reason. Data for the old, well-tried materials are established, reliable, and easily found. Data for newer, emerging, materials may be incomplete or untrustworthy. Yet innovation is often made possible by new materials. So it is important to know how to judge data quality. Consider the Figure below. On the left a material is tested and the data are captured. But these raw data—unqualified numbers—are, for our purposes, useless. To make data useful requires statistical analysis. What is the mean value of the property when measured on a large batch of samples? What is the standard deviation? Given these, it is possible to calculate allowables: values of properties that, with a given certainty (say, one part

in 106) can be guaranteed. Material texts generally present test data; by contrast, data in most engineering handbooks are allowables.

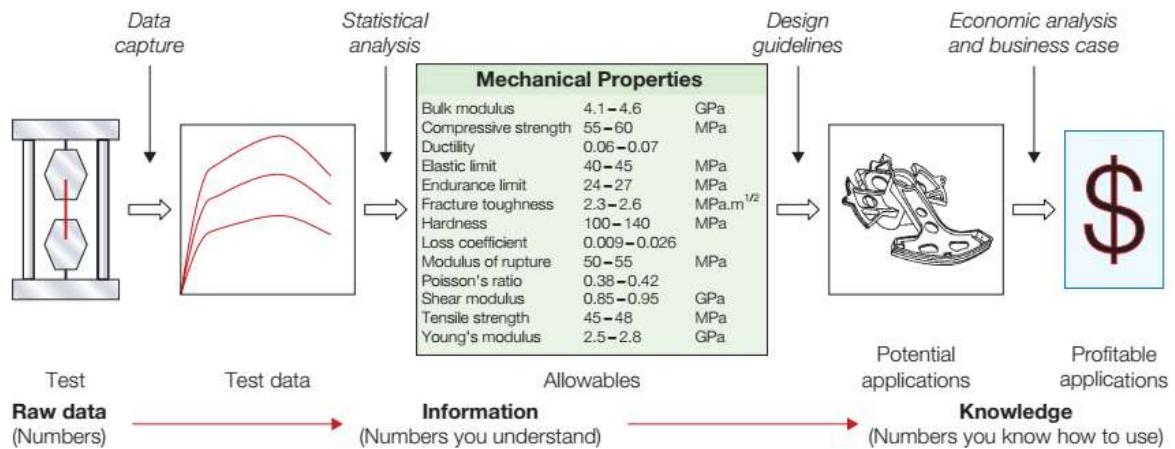


Figure 4: Types of material information. We are interested here in the types found in the center of this schematic: structured data for design “allowables” and the characteristics of a material that relate to its ability to be formed, joined, and finished; records of experience with its use; and design guidelines for its use.

One can think of data with known precision and provenance as information. Information can generally be reported as tables of numbers, as yes/no statements or as rankings: that is, it can be structured. Many attributes that can be structured are common to all materials; all have a density, an elastic modulus, a strength, a thermal conductivity. Structured information can be stored in a database and—since all materials have values—it is the starting point for selecting between them.

This is a step forward, but it is not enough. To design with a material, you need to know its real character, its strengths, and its weaknesses. How do you shape it? How do you join it? Who has used it before and for what? Did it fail? Why? This information exists in handbooks, is documented as design guidelines, and is reported in failure analyses and case studies. It consists largely of text, graphs and images, and while certain bits of it may be available for one material, for another they may not. It is messier, but it is essential in reaching a final selection. We refer to this supporting information as documentation.

Data exist that meet the needs of all these levels. Each level requires its own data management scheme. The management system must be design-led, yet must recognize the richness of choice and embrace the complex interaction between the material, its shape, the process by which it is given that shape, and the function it is required to perform. And it must allow rapid iteration—back-looping when a particular path proves to be unprofitable.

Materials Databases

- Matmatch
- ASM international
- Material Connexion
- Materials Web
- UL Prospector
- Materials Project

Chemspider
 Makeitfrom
 MatNavi NIMS material database
 MatWeb
 MatDat

Engineering Materials and Their Properties:

The classes of engineering materials and their structure

It is conventional to classify the materials of engineering into the six broad families: metals, polymers, elastomers, ceramics, glasses, and hybrids shown in Figure.

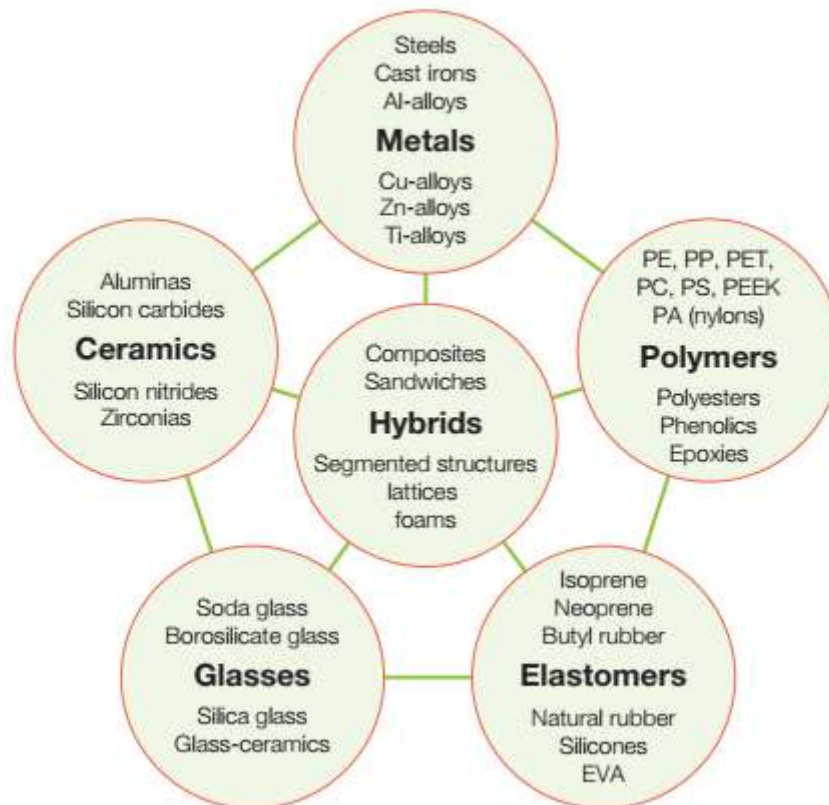


Figure 5: The menu of engineering materials. The basic families of metals, ceramics, glasses, polymers, and elastomers can be combined in various geometries to create hybrids

Metals are stiff. They have relatively high elastic moduli. Most, when pure, are soft and easily deformed. They can be made strong by alloying and by mechanical and heat treatment, but they remain ductile, allowing them to be formed by deformation processes. Certain high-strength alloys (spring steel, for instance) have ductilities as low as 1%, but even this is enough to ensure that the material yields before it fractures and that fracture, when it occurs, is of a tough, ductile type. Partly because of their ductility, metals are prey to fatigue and of all the classes of material, they are the least resistant to corrosion.

Ceramics, too, have high moduli, but unlike metal, they are brittle. Their “strength” in tension means the brittle fracture strength; in compression it is the brittle crushing strength, which is

about 15 times greater. And because ceramics have no ductility, they have a low tolerance for stress concentrations (like holes or cracks) or for high-contact stresses (at clamping points, for instance). Ductile materials accommodate stress concentrations by deforming in a way that redistributes the load more evenly, and because of this, they can be used under static loads within a small margin of their yield strength. Ceramics cannot. Brittle materials always have a wide scatter in strength, and the strength itself depends on the volume of material under load and the time over which it is applied. So ceramics are not as easy to design with as metals. Despite this, they have attractive features. They are stiff, hard, and abrasion-resistant (hence their use for bearings and cutting tools); they retain their strength to high temperatures; and they resist corrosion well

Glasses are noncrystalline (“amorphous”) solids. The most common are the soda-lime and borosilicate glasses familiar as bottles and ovenware, but there are many more. Metals, too, can be made noncrystalline by cooling them sufficiently quickly. The lack of crystal structure suppresses plasticity, so, like ceramics, glasses are hard, brittle, and vulnerable to stress concentrations.

Polymers are at the other end of the spectrum. They have moduli that are low, roughly 50 times lower than those of metals, but they can be strong—nearly as strong as metals. A consequence of this is that elastic deflections can be large. They creep, even at room temperature, meaning that a polymer component under load may, with time, acquire a permanent set. And their properties depend on temperature so that a polymer that is tough and flexible at 20°C may be brittle at the 4°C of a household refrigerator, yet may creep rapidly at the 100°C of boiling water. Few have useful strength above 200°C. Some polymers are mainly crystalline, some are amorphous (noncrystalline), some are a mix of crystalline and amorphous—transparency goes with the amorphous structure. If these aspects are allowed for in the design, the advantages of polymers can be exploited. And there are many. When combinations of properties, such as strength per unit weight, are important, polymers can compete with metals. They are easy to shape. Complicated parts performing several functions can be molded from a polymer in a single operation. The large elastic deflections allow the design of polymer components that snap together, making assembly fast and cheap. And by accurately sizing the mold and precoloring the polymer, no finishing operations are needed. Polymers resist corrosion (paints, for instance, are polymers) and have low coefficients of friction. Good design exploits these properties.

Elastomers are long-chain polymers above their glass-transition temperature, T_g . The covalent bonds that link the units of the polymer chain remain intact, but the weaker Van der Waals and hydrogen bonds that, below T_g , bind the chains to each other, have melted. This gives elastomers unique properties: Young’s moduli as low as 10^{-3} GPa (10^5 times less than that typical of metals) increase with temperature (all other solids show a decrease), and have enormous elastic extension. Their properties differ so much from those of other solids that special tests have evolved to characterize them.

Hybrids are combinations of two or more materials in a predetermined configuration and scale. They combine the attractive properties of the other families of materials while avoiding some of their drawbacks. The family of hybrids includes fiber and particulate composites, sandwich structures, lattice structures, foams, cables, and laminates; almost all the materials of nature—wood, bone, skin, and leaf—are hybrids. Fiber-reinforced composites are, of course, the most

familiar. Most of those at present available to the engineer have a polymer matrix reinforced by fibers of glass, carbon, or Kevlar (an aramid). They are light, stiff, and strong, and they can be tough. They, and other hybrids using a polymer as one component, cannot be used above 250°C because the polymer softens, but at room temperature their performance can be outstanding. Hybrid components are expensive, and they are relatively difficult to form and join.

Material properties:

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. Property profiles are assembled by systematic testing.

Mechanical properties

The elastic modulus, E (units: GPa or GN/m²), is the slope of the initial, linear-elastic, part of the stress-strain curve (Figure 6). Young's modulus, E , describes response to tensile or compressive loading; the shear modulus, G , describes response to shear loading; and the bulk modulus, K , describes the response to hydrostatic pressure. Poisson's ratio, ν , is the negative of the ratio of the lateral strain, ϵ_2 , to the axial strain, ϵ_1 , in axial loading

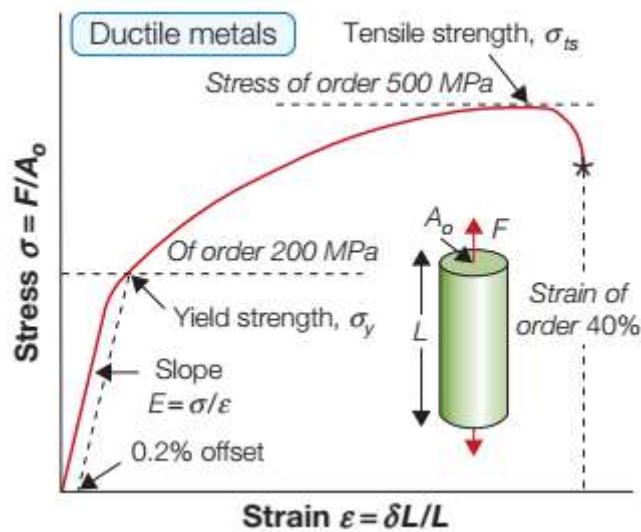


Figure 6: The stress-strain curve for a metal, showing the modulus, E , the 0.2% yield strength, σ_y , and the ultimate strength, σ_{ts}

$$\nu = -\frac{\epsilon_2}{\epsilon_1}$$

Accurate moduli are measured dynamically: by exciting the natural vibrations of a beam or a wire or by measuring the velocity of sound waves in the material.

In an isotropic material, the moduli are related in the following ways:

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

The strength, σ_f (units: MPa or MN/m²), of a solid requires careful definition. For metals, we identify σ_f with the 0.2% offset yield strength σ_y (see Figure 6), that is, the stress at which the stress-strain curve for axial loading deviates by a strain of 0.2% from the linear-elastic line. It is the same in tension and compression.

For polymers, σ_f is identified as the stress at which the stress-strain curve becomes markedly nonlinear, at a strain typically of 1% (Figure 7). This may be caused by shear yielding: the irreversible slipping of molecular chains; or it may be caused by crazing: the formation of low-density, crack-like volumes that scatter light, making the polymer look white. Polymers are a little stronger ($\approx 20\%$) in compression than in tension.

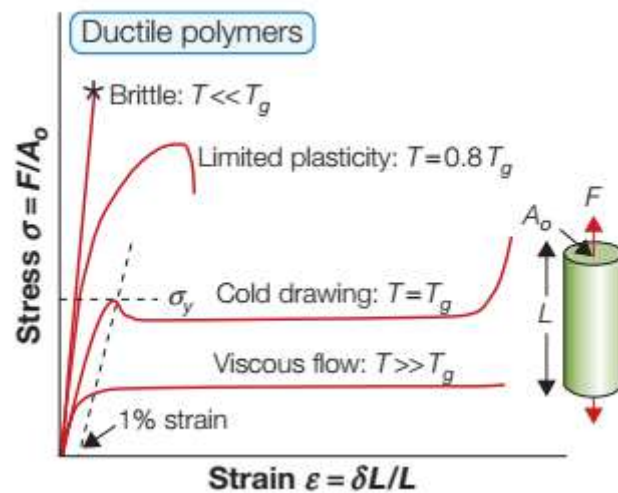


Figure 7: Stress-strain curves for a polymer below, at, and above its glass transition temperature, T_g .

Strength, for ceramics and glasses, depends strongly on the mode of loading (Figure 8). In tension, strength means the fracture strength, σ_t . In compression it means the crushing strength σ_c , which is much greater; typically

$$\sigma_c = 10 \text{ to } 15 \sigma_t$$

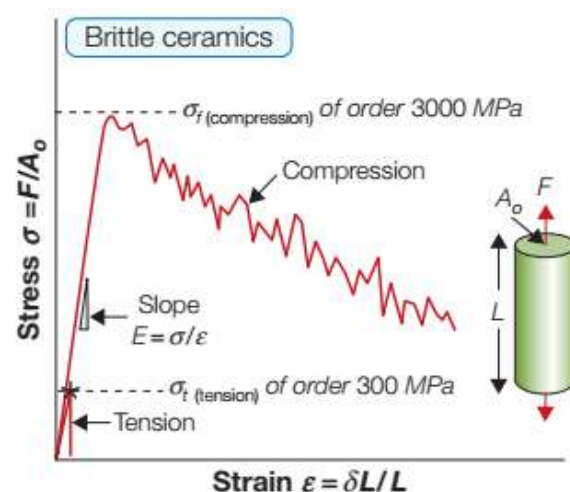


Figure 8: Stress-strain curves for a ceramic in tension and in compression. The compressive strength, σ_c , is 10 to 15 times greater than the tensile strength, σ_t .

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} (units: MPa) is the maximum surface stress in a bent beam at the instant of failure (Figure 9). One might expect this to be the same as the strength measured in tension, but for ceramics it is greater by a factor of about 1.3 because the volume subjected to this maximum stress is small and the probability of a large flaw lying in it is small also; in simple tension all flaws see the same stress.

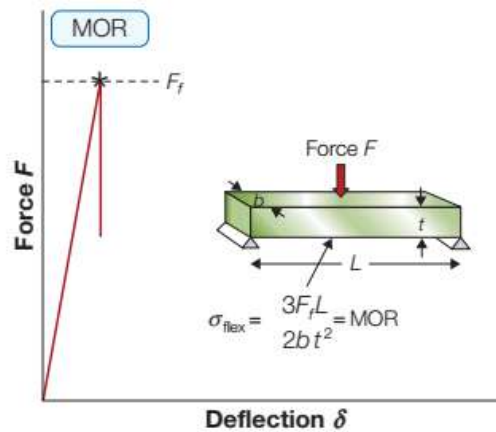


Figure 9: The modulus of rupture (MOR) is the surface stress at failure in bending. It is equal to, or slightly larger than, the failure stress in tension.

The strength of a composite is best defined by a set deviation from linear-elastic behavior; often an offset of 0.5% is taken. Composites that contain fibers, including natural composites such as wood, are a little weaker (up to 30%) in compression than tension because fibers buckle. In subsequent chapters, σ_f for composites means the tensile strength.

The tensile (or ultimate) strength σ_{ts} (units: MPa) is the nominal stress at which a round bar of the material, loaded in tension, separates (Figure 6). For brittle solids—ceramics, glasses, and brittle polymers—it is the same as the failure strength in tension. For metals, ductile polymers, and most composites, it is greater than the yield strength, σ_y , by a factor of between 1.1 and 3 because of work hardening or, in the case of composites, load transfer to the reinforcement.

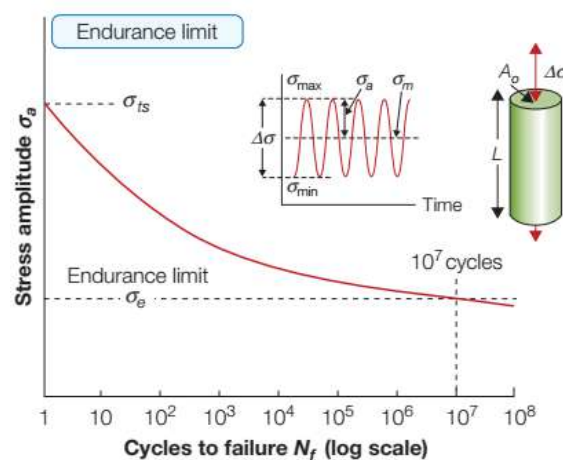


Figure 10: Fatigue curve

Cyclic loading can cause a crack to nucleate and grow in a material, culminating in fatigue failure. For many materials there exists a fatigue or endurance limit, σ_e (units: MPa), illustrated by the $\Delta\sigma - N_f$ curve of Figure 10. It is the stress amplitude $\Delta\sigma$ below which fracture does not occur, or occurs only after a very large number ($N_f > 10^7$) of cycles.

The hardness, H (SI units: MPa) of a material is measured by pressing a pointed diamond or hardened steel ball into the material's surface (Figure 11). The hardness is defined as the indenter force divided by the projected area of the indent. Vickers H_v scale with units of kg/mm^2 .

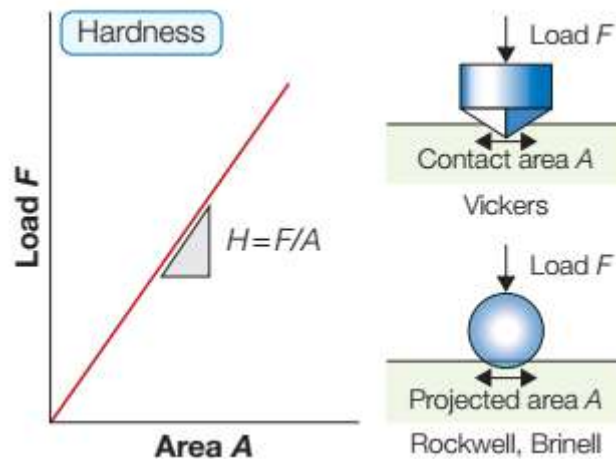


Figure 11: Hardness is measured as the load, F , divided by the projected area of contact, A , when a diamond-shaped indenter is forced into the surface.

The toughness, G_{1c} (units: kJ/m^2), and the fracture toughness, K_{1c} (units: $\text{MPa/m}^{1/2}$ or $\text{MN/m}^{1/2}$), measure the resistance of a material to the propagation of a crack. The fracture toughness is measured by loading a sample containing a deliberately introduced crack of length $2c$ (Figure 11).

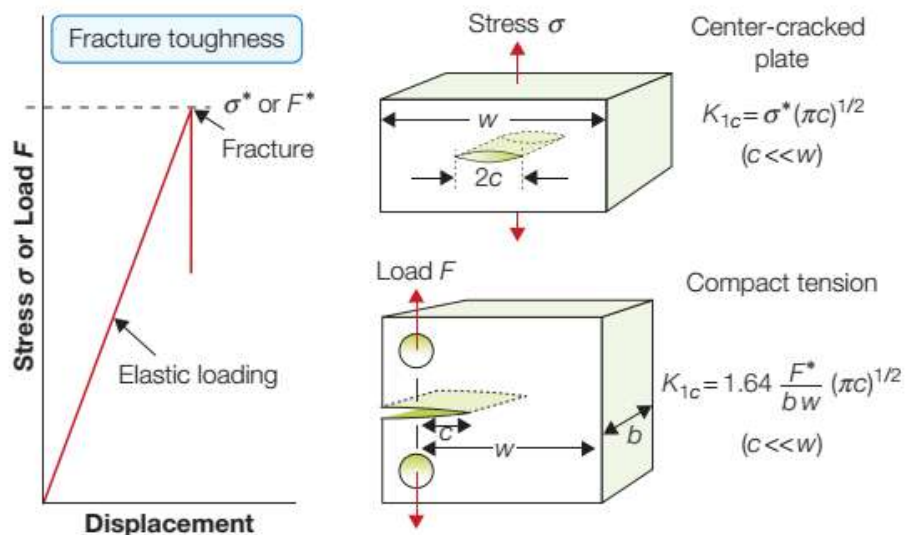


Figure 11: The fracture toughness, K_{1c} , measures the resistance to the propagation of a crack. The test specimen containing a crack of length $2c$ fails at stress σ^* . The fracture toughness is then $K_{1c} = Y\sigma^*\sqrt{\pi c}$ where Y is a constant near unity.

Wear, the loss of material when surfaces slide against each other, is a multibody problem. Nevertheless, it can, to a degree, be quantified. When solids slide (Figure 12), the volume of material lost from one surface, per unit distance slid, is called the wear rate, W (units: m^2).

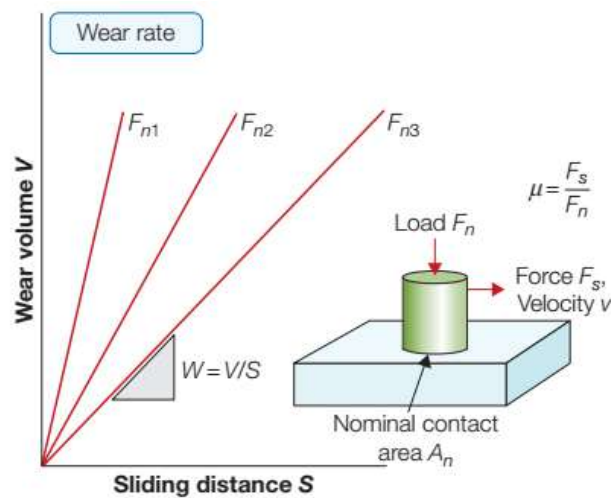


Figure 12: Wear is the loss of material from surfaces when they slide. The wear resistance is measured by the Archard wear constant, KA , defined in the text.

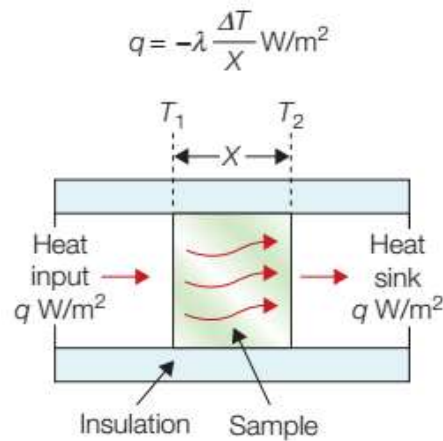
Functional properties

Thermal properties

Two temperatures, the melting temperature, T_m , and the glass temperature, T_g (units for both: K or C), 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 temperature T_g characterizes the transition from true solid to very viscous liquid. It is helpful, in engineering design, to define two further temperatures: the maximum and minimum service temperature, T_{max} and T_{min} (both: K or C). The first tells us the highest temperature at which the material can reasonably be used without oxidation, chemical change, or excessive creep becoming a problem. The second is the temperature below which the material becomes brittle or otherwise unsafe to use.

The **heat capacity** or specific heat (units J/kg.K) is the energy to heat 1 kg of a material by 1 K. The measurement is usually made at constant pressure (atmospheric pressure) so it is given the symbol C_p . The heat capacity is measured by calorimetry which is also the standard way of measuring the glass temperature, T_g . A measured quantity of energy (here, electrical energy) is pumped into a sample of material of known mass. The temperature rise is measured, allowing the energy/kg.K to be calculated

The rate at which heat is conducted through a solid at steady state (meaning that the temperature profile does not change with time) is measured by the **thermal conductivity**, λ (units: W/m.K).



When heat flow is transient, the flux depends instead on the thermal diffusivity, a (units: m^2/s), defined by

$$a = \frac{\lambda}{\rho C_p}$$

where ρ is the density and C_p is the heat capacity. The thermal diffusivity can be measured directly by measuring the decay of a temperature pulse when a heat source, applied to the material, is switched off; or it can be calculated from λ , via the last equation.

The thermal strain per degree of temperature change is measured by the **linear thermal expansion coefficient**, α (units: K^{-1} or, more conveniently, “microstrain/ $^\circ\text{C}$ ” or $10^{-6}^\circ\text{C}^{-1}$).

The **thermal shock resistance** ΔT_s (units: K or $^\circ\text{C}$) is the maximum temperature difference through which a material can be quenched suddenly without damage.

Creep is the slow, time-dependent deformation that occurs when materials are loaded above about $\frac{1}{3} T_m$ or $\frac{2}{3} T_g$. Here we rely instead on avoiding the use of a material above its maximum service temperature, T_{max} , or, for polymers, the “**heat deflection temperature.**”

Electrical properties

The electrical resistivity, ρ_e (SI units $\Omega\cdot\text{m}$ or, commonly, $\mu\Omega\cdot\text{cm}$), is the resistance of a unit cube with unit potential difference between a pair of its faces. It has an immense range, from a little more than 10^{-8} in units of $\Omega\cdot\text{m}$ for good conductors (equivalent to $1 \mu\Omega\cdot\text{cm}$) to more than $10^{16} \Omega\cdot\text{m}$ ($10^{24} \mu\Omega\cdot\text{cm}$) for the best insulators. The electrical conductivity, κ_e (units Siemens per meter, S/m or $(\Omega\cdot\text{m})^{-1}$), is simply the reciprocal of the resistivity.

When an insulator (or dielectric) is placed in an electric field, it becomes polarized and charges appear on its surfaces that tend to screen the interior from the electric field. The tendency to polarize is measured by the dielectric constant, ϵ_r , a dimensionless quantity. Most insulators have values between 2 and 30, though low-density foams approach the value 1.

The **breakdown potential** (units: MV/m) is the electrical potential gradient at which an insulator breaks down and a damaging surge of current flows through it. It is measured by

increasing, at a uniform rate, a 60-Hz alternating potential applied across the faces of a plate of the material until breakdown occurs, typically at a potential gradient between 1 and 100 million volts per meter (units: MV/m).

Optical properties

All materials allow for some passage of light, although for metals it is exceedingly small. The speed of light when in the material, v , is always less than that in vacuum, c . A consequence is that 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 (dimensionless), is

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

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. When $n = 1$, the entire incident intensity enters the material, but when $n > 1$, some is reflected. If the surface is smooth and polished, it is reflected as a beam; if rough, it is scattered. The percentage reflected, R , is related to the refractive index by

$$R = \left(\frac{n - 1}{n + 1} \right)^2 \times 100$$

As n increases, the value of R approaches 100%.

Eco-properties

The embodied energy (units MJ/kg) is the energy required to extract 1 kg of a material from its ores and feedstock. The associated CO₂ footprint (units: kg/kg) is the mass of carbon dioxide released into the atmosphere during the production of 1 kg of material.

Material Selection Charts:

Selection criteria for materials

One of the most challenging task of materials engineer is the proper selection of the material for a particular job, e.g., a particular component of a machine or structure. An engineer must be in a position to choose the optimum combination of properties in a material at the lowest possible cost without compromising the quality.

Factors affecting the selection of materials:

(i) Component shape:

The shape and size of a component has great effect on the choice of the processing unit which ultimately effects the choice of the material. To make it more clear, we consider an example, let the best possible production method is selected, under given conditions, it is *die casting*, obviously, now the choice of the material becomes limited, i.e. one can only

choose materials with lower melting points, e.g. *aluminium, zinc, magnesium* and *thermoplastics*.

(ii) Dimensional tolerance:

There are some materials which can be finished to close tolerance while others cannot. Obviously, the required dimensional tolerance for finished components will, influence the choice of materials.

(iii) Mechanical properties:

To select a suitable material for specific conditions, all mechanical properties, e.g., toughness, hardness, strength, etc. guide us.

(iv) Fabrication (Manufacturing) requirements:

Method of processing of the material also affects the properties of a component, e.g., *forged components* can be stronger than the *casted components*. Different types of working processes may also give different types of fibre structure. However, investment casting can provide precise dimensions at low cost in comparison to machine operations.

(v) Service requirements:

Service requirements are :

- ✓ dimensional stability,
- ✓ strength,
- ✓ toughness,
- ✓ heat resistance,
- ✓ corrosion resistance,
- ✓ fatigue and creep resistance,
- ✓ electrical and thermal conductivity etc.

(vi) Cost :

(A) Cost of the material:

In most of the cases, the cost of raw material accounts about 50 % of the finished cost. Obviously, the cost of the material is a major factor which influences the choice of the material or process. We must note that the use of cheaper material will not always reduce the final cost of the component or product. Use of cheaper material may be associated with higher processing cost due to large number of operations to be performed and also more scrap. We can easily see that this sometimes makes the overall cost more than that of expensive raw material in combination with low processing cost due to lesser number of operations and lesser scrap. The type of material affects the detailed aspect of design and hence the choice of material as well as the process is selected at the early design state e.g. whether the material is to be joined by spot welding, screws or rivetes, must be decided at the design state

(B) Cost of processing:

In most of the industries, the processing cost (labour cost) and other costs such as overhead costs account for about 50% of the production cost. Overhead cost in automatic

industries is much more than the other costs. If one can somehow reduce all such costs, the total production cost will automatically reduce.

(vii) Availability of the material:

We may find that sometimes the availability of the material becomes a governing factor. When the desired material supply is limited, then a costly material which is available in ample quantity may be chosen

Material property Charts

- The modulus–density chart
- The strength–density chart
- The modulus–strength chart
- The specific stiffness–specific strength chart
- The fracture toughness–modulus chart
- The fracture toughness–strength chart

The fracture toughness–strength chart

Modulus and density are familiar properties. Steel is stiff; rubber is compliant: These are effects of modulus. Lead is heavy; cork is buoyant: these are effects of density. Figure 13 shows the range of Young’s modulus, E , and density, ρ , for engineering materials. Data for members of a particular family of materials cluster together and can be enclosed by a colored envelope

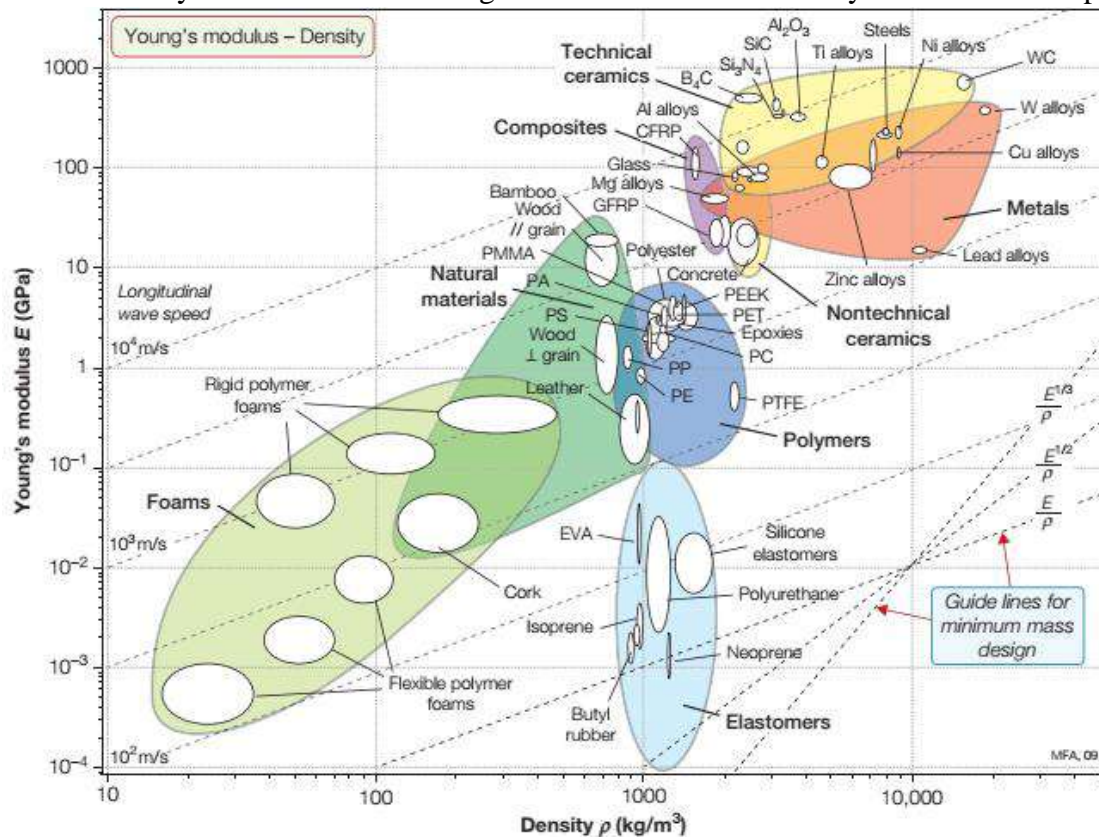


Figure 13: Young’s modulus E plotted against density ρ . The heavy envelopes enclose data for a given class of material. The diagonal contours show the longitudinal wave velocity. The guide lines of constant E/ρ , $E^{1/2}/\rho$, and $E^{1/3}/\rho$ allow selection of materials for minimum weight, deflection-limited, design.

Here, one property (the modulus, E , in this case) is plotted against another (the density, ρ). The range of the axes is chosen to include all materials, from the lightest, flimsiest foams to the stiffest, heaviest metals, and it is large, again requiring log scales. It is found that data for a given family of materials (polymers, for example) cluster together; the subrange associated with one material family is, in all cases, much smaller than the full range of that property.

The speed of sound in a solid depends on E and ρ ; the longitudinal wave speed v , for instance, is

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

or (taking logs)

$$\log E = \log \rho + 2 \log v$$

For a fixed value of v , this equation plots as a straight line of slope 1. This allows us to add contours of constant wave velocity to the chart: They are the family of parallel diagonal lines, linking materials in which longitudinal waves travel with the same speed.

The density of a solid depends on the atomic weight of its atoms or ions, their size, and the way they are packed. The size of atoms does not vary much: Most have a volume within a factor of two of $2 \times 10^{-29} \text{ m}^3$. Packing fractions do not vary much either—a factor of two more or less. Close packing gives a packing fraction of 0.74; open networks such as that of the diamond-cubic structure give about 0.34. The spread of density comes mainly from the spread of atomic weight, ranging from 1 for hydrogen to 238 for uranium. Metals are dense because they are made of heavy atoms, packed closely together; polymers have low densities because they are largely made of carbon (atomic weight: 12) and hydrogen (atomic weight: 1) in more open amorphous or crystalline packings. Ceramics, for the most part, have lower densities than metals because they contain light O, N or C atoms. Even the lightest atoms, packed in the most open way, give solids with a density of around 1000 kg/m^3 , the same as that of water. Materials with lower densities than this are foams—materials made up of cells containing a large fraction of pore space. The moduli of most materials depend on two factors: bond stiffness and the number of bonds per unit volume. A bond is like a spring, and, like a spring, it has a spring constant, S (units: N/m). Young's modulus, E , is roughly

$$E = \frac{S}{r_0}$$

where r_0 is the “atom size” (r_0^3 is the mean atomic or ionic volume). The wide range of moduli is largely caused by the range of values of S . The covalent bond is stiff ($S = 20\text{--}200 \text{ N/m}$); the metallic and the ionic a little less so ($S = 15\text{--}100 \text{ N/m}$). Diamond has a very high modulus because the carbon atom is small, giving a high bond density, and its atoms are linked by strong covalent springs ($S = 200 \text{ N/m}$). Metals have high moduli because close packing gives a high bond density and the bonds are strong, though not as strong as those of diamond. Polymers contain both strong diamond-like covalent bonds and weak hydrogen or Van der Waals bonds ($S = 0.5\text{--}2 \text{ N/m}$). It is the weak bonds that stretch when the polymer is deformed, giving low moduli.

Elastomers have a low E because their weak secondary bonds have melted as their glass temperature, T_g , is below room temperature, leaving only the very weak “entropic” restoring

force associated with tangled, long-chain molecules. Foams have low moduli because the cell walls bend easily when the material is loaded.

The chart helps in the common problem of material selection for applications in which mass must be minimized. Their use in selecting materials for stiffness-limited design at minimum weight

The strength–density chart

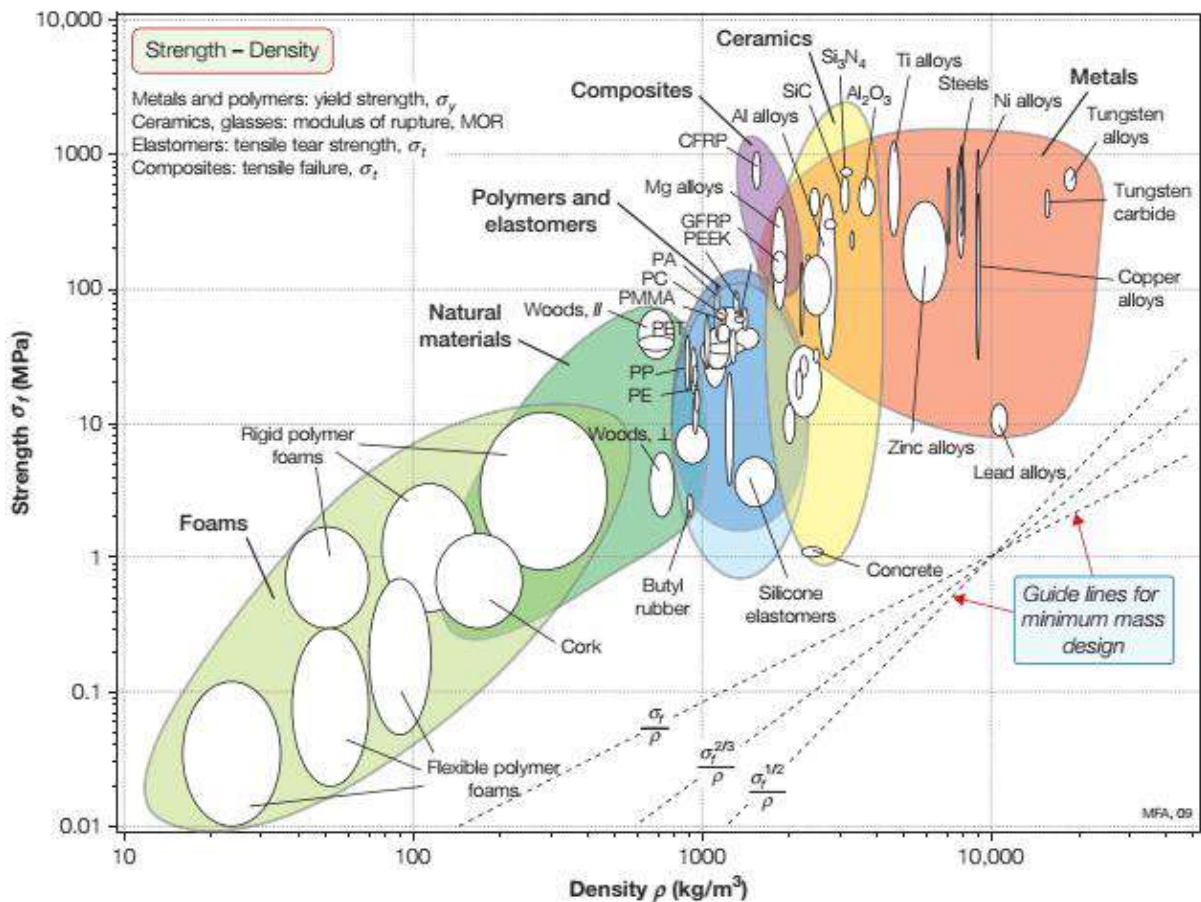


Figure 14: Strength σ_f plotted against density ρ (yield strength for metals and polymers, compressive strength for ceramics, tear strength for elastomers, and tensile strength for composites). The guide lines of constants σ_f / ρ , $\sigma_f^{2/3} / \rho$, and $\sigma_f^{1/2} / \rho$ are used in minimum weight, yield-limited, design.

For metals and polymers, it is the yield strength, but since the range of materials includes those that have been worked or hardened in some other way as well as those that have been softened by annealing, the range is large. For brittle ceramics, the strength plotted here is the modulus of rupture: the flexural strength. It is slightly greater than the tensile strength, but much less than the compression strength, which for ceramics is 10 to 15 times greater than the strength in tension. For elastomers, strength means the tensile tear strength. For composites, it is the tensile failure strength (the compressive strength can be less by up to 30% because of fiber buckling). The symbol σ_f for all of these strengths.

The single most important concept in understanding this wide range is the lattice resistance or Peierls stress. It is the intrinsic resistance of the structure to plastic shear. Plastic shear in a

crystal involves the motion of dislocations. Pure metals are soft because the nonlocalized metallic bond does little to hinder dislocation motion, whereas ceramics are hard because their more localized covalent and ionic bonds (which must be broken and reformed when the structure is sheared) lock the dislocations in place. In the case of noncrystalline solids if the unit step involves breaking strong bonds (as in an inorganic glass), the materials will be strong. If it only involves the rupture of weak bonds (the Van der Waals bonds in polymers for example), it will be weak.

When the lattice resistance is low, the material can be strengthened by introducing obstacles to slip. In metals this is achieved by adding alloying elements, particles, grain boundaries, and other dislocations (“work hardening”); in polymers, by cross-linking or by orienting the chains so that strong covalent bonds, as well as weak Van der Waals bonds, must be broken when the material deforms. When, on the other hand, the lattice resistance is high, further hardening is superfluous—the problem becomes that of suppressing fracture.

An important use of the chart is in materials selection for lightweight strength-limited design. Guide lines are shown for materials selection in the minimum-weight design of ties, columns, beams, and plates, and for yield-limited design of moving components in which inertial forces are important.

The modulus–strength chart

High tensile steel makes good springs. But so does rubber. How is it that two such different materials are both suited to the same task?. It shows Young’s modulus, E , plotted against strength, σ_f .

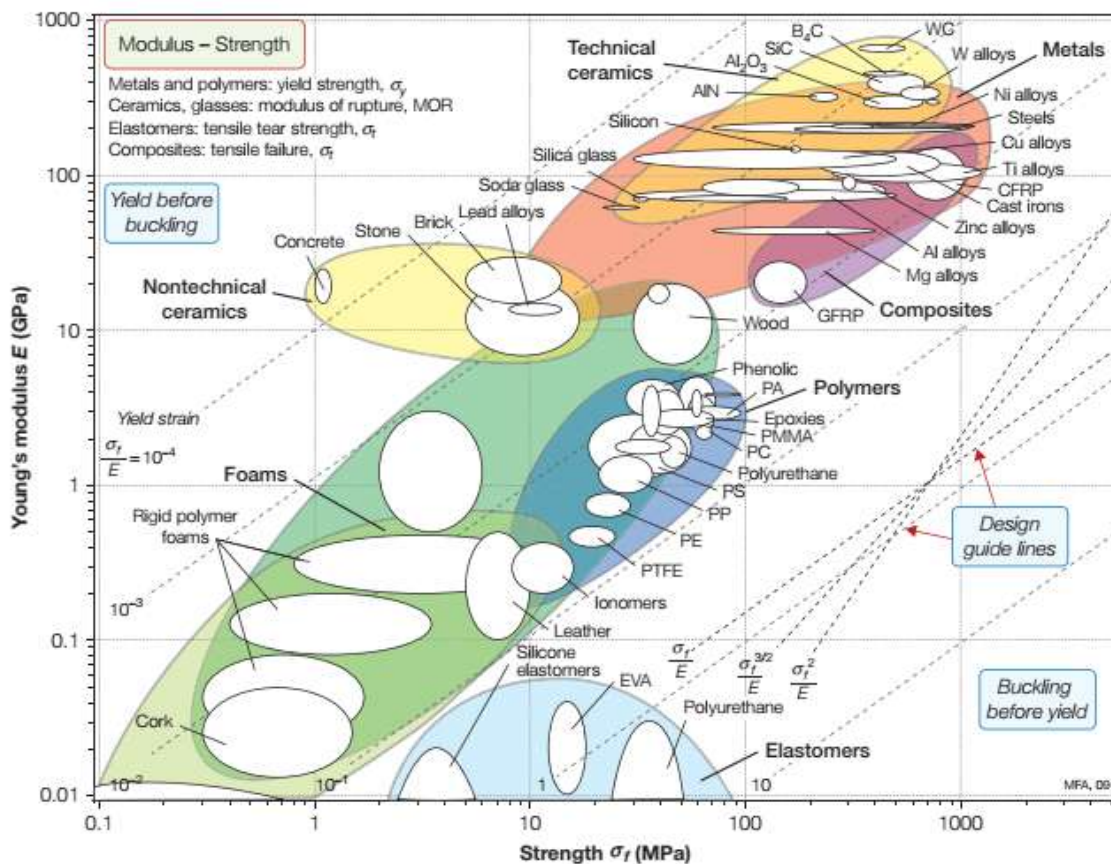


Figure 15: Young’s modulus E plotted against strength σ_f . The design guide lines help with the selection of materials for springs, pivots, knife-edges, diaphragms, and hinges

Contours of yield strain or fracture strain, σ_f/E (meaning the strain at which the material ceases to be linearly elastic), appear as a family of straight parallel lines. Examine these first. Engineering polymers have large yield strains of between 0.01 and 0.1; the values for metals are at least a factor of 10 smaller. Composites and woods lie on the 0.01 contour, as good as the best metals. Elastomers, because of their exceptionally low moduli, have values of σ_f/E larger than any other class of material: typically, 1 to 10.

The specific stiffness–specific strength chart

Many designs, particularly those for things that move, call for stiffness and strength at minimum weight. Figure 16 shows E/ρ plotted against σ_f/ρ . These are measures of “mechanical efficiency,” meaning the use of the least mass of material to do the most structural work.

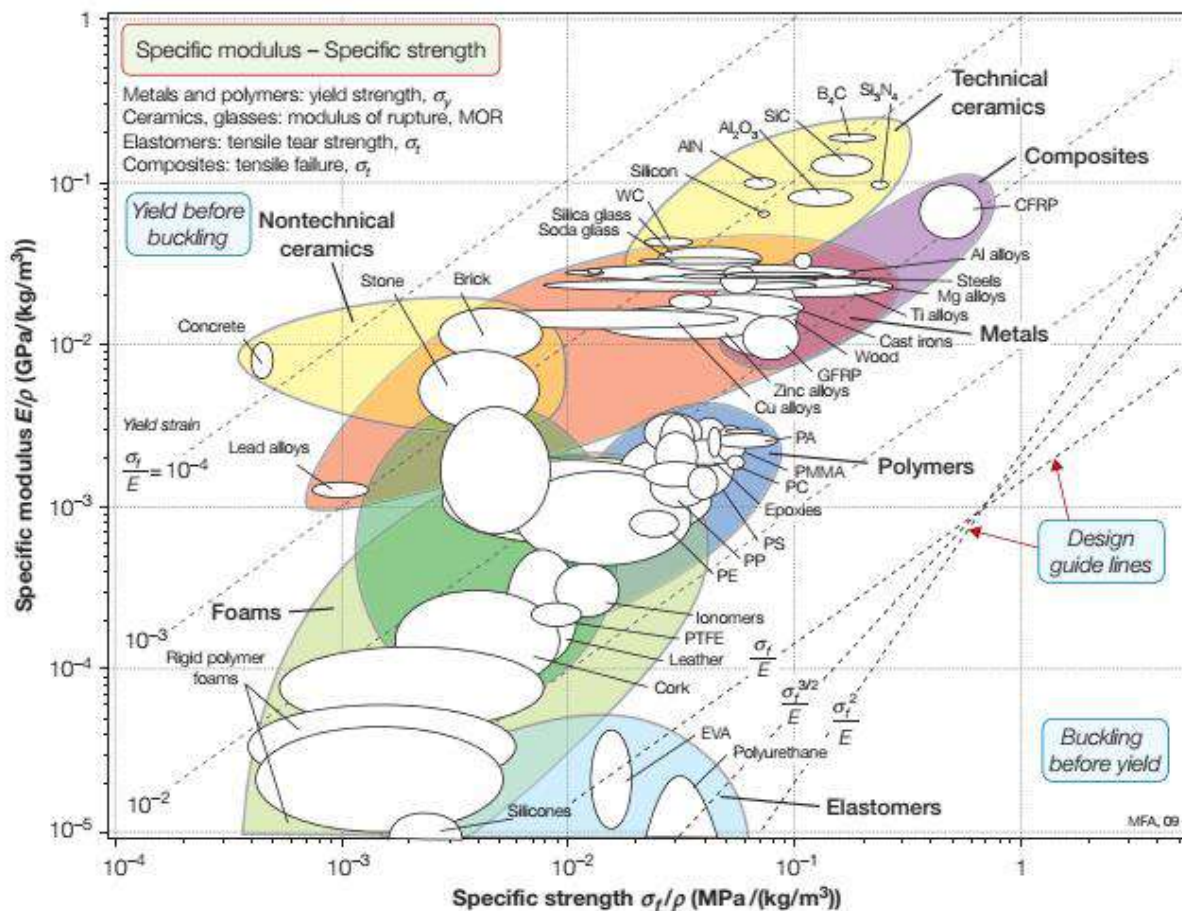


Figure 16: Specific modulus E/ρ plotted against specific strength σ_f/ρ . The design guide lines help with the selection of materials for lightweight springs and energy-storage systems.

Composites, particularly CFRP, lie at the upper right. They emerge as the material class with the most attractive specific properties, one of the reasons for their increasing use in aerospace. Ceramics have exceptionally high stiffness per unit weight, and their strength per unit weight is as good as that of metals, but their brittleness excludes them from much structural use. Metals are penalized because of their relatively high densities. Polymers, because their densities are low. Chart 16 has application in selecting materials for light springs and energy storage devices.

The fracture toughness–modulus chart

Increasing the strength of a material is useful only as long as the material remains plastic and does not become brittle; if it does, it is vulnerable to failure by fast fracture initiated from any tiny crack or defect it may contain. The resistance to the propagation of a crack is measured by the fracture toughness, K_{1c} , the units of which are $\text{MPa}\cdot\text{m}^{1/2}$. It is plotted against modulus E in Figure 17.

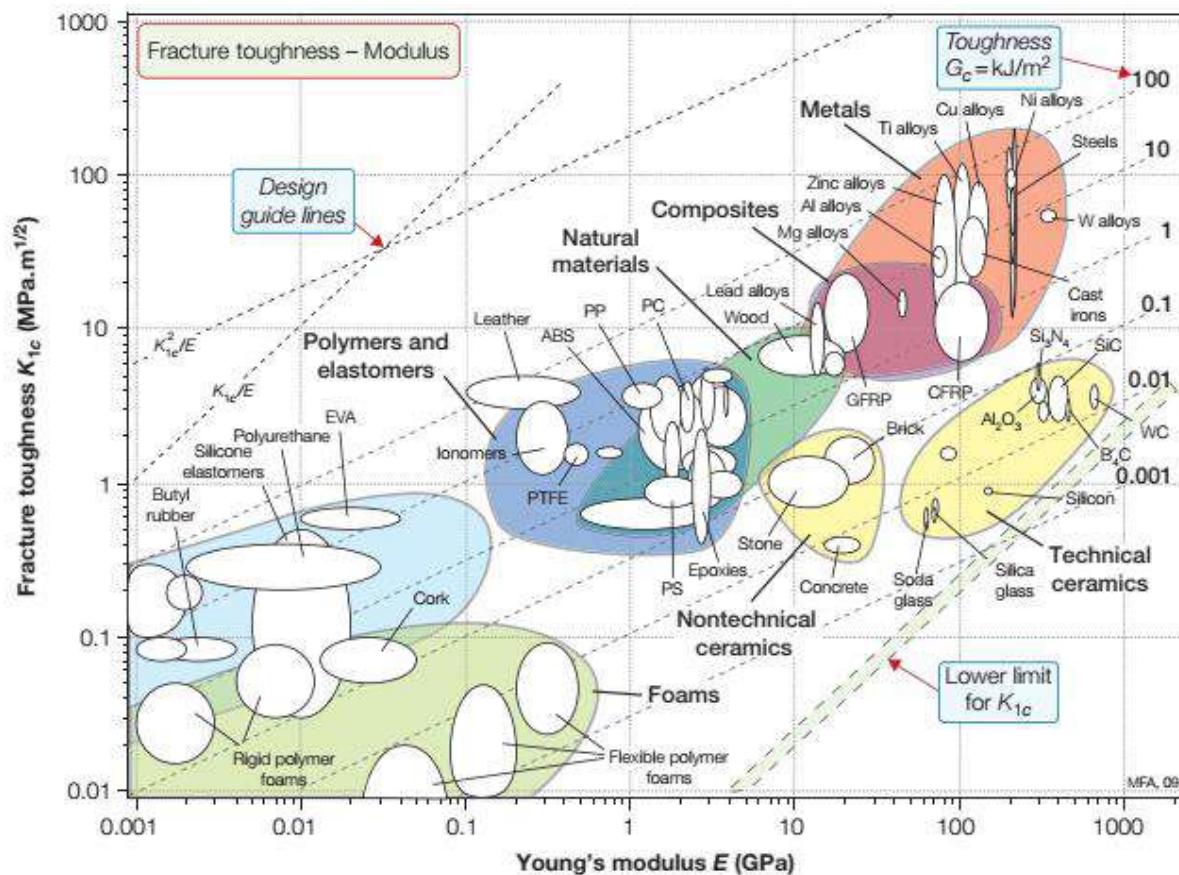


Figure 17: Fracture toughness K_{1c} plotted against Young's modulus E . The family of lines is of constant K_{1c}^2/E (approximately G_{1c} , the fracture energy or toughness). These, and the guide line of constant K_{1c}/E , help in design against fracture. The shaded band shows the lower limit for K_{1c} .

Values range from less than 0.01 to over 100 $\text{MPa}\cdot\text{m}^{1/2}$. At the lower end of this range are brittle materials, which, when loaded, remain elastic until they fracture. For these, linear-elastic fracture mechanics works well, and the fracture toughness itself is a well-defined property. The figure shows one reason for the dominance of metals in engineering; they almost all have values of K_{1c} above 18 $\text{MPa}\cdot\text{m}^{1/2}$, a value often quoted as a minimum for conventional design. The lower limit of K_{1c} is plotted as a shaded band near the lower right corner of the chart 17. The most brittle ceramics lie close to the threshold. Metals, polymers, and composites fracture, the energy absorbed is vastly greater, usually because of plasticity associated with crack propagation.

Plotted on Figure 17 are contours of toughness, G_c , a measure of the apparent fracture surface energy ($G_c \approx K_{1c}^2/E$). The true surface energies, γ , of solids lie in the range 10⁻⁴ to 10⁻³ kJ/m^2 . The diagram shows that the values of the toughness start at 10⁻³ kJ/m^2 and range through

almost five decades to over 100 kJ/m². On this scale, ceramics (10⁻³–10⁻¹ kJ/m²) are much lower than polymers (10⁻¹–10 kJ/m²); this is part of the reason polymers are more widely used in engineering than ceramics.

The fracture toughness–strength chart

The stress concentration at the tip of a crack generates a process zone: a plastic zone in ductile solids, a zone of micro-cracking in ceramics, and a zone of delamination, debonding, and fiber pull-out in composites. Within the process zone, work is done against plastic and frictional forces; it is this that accounts for the difference between the measured fracture energy, G_c , and the true surface energy 2γ .

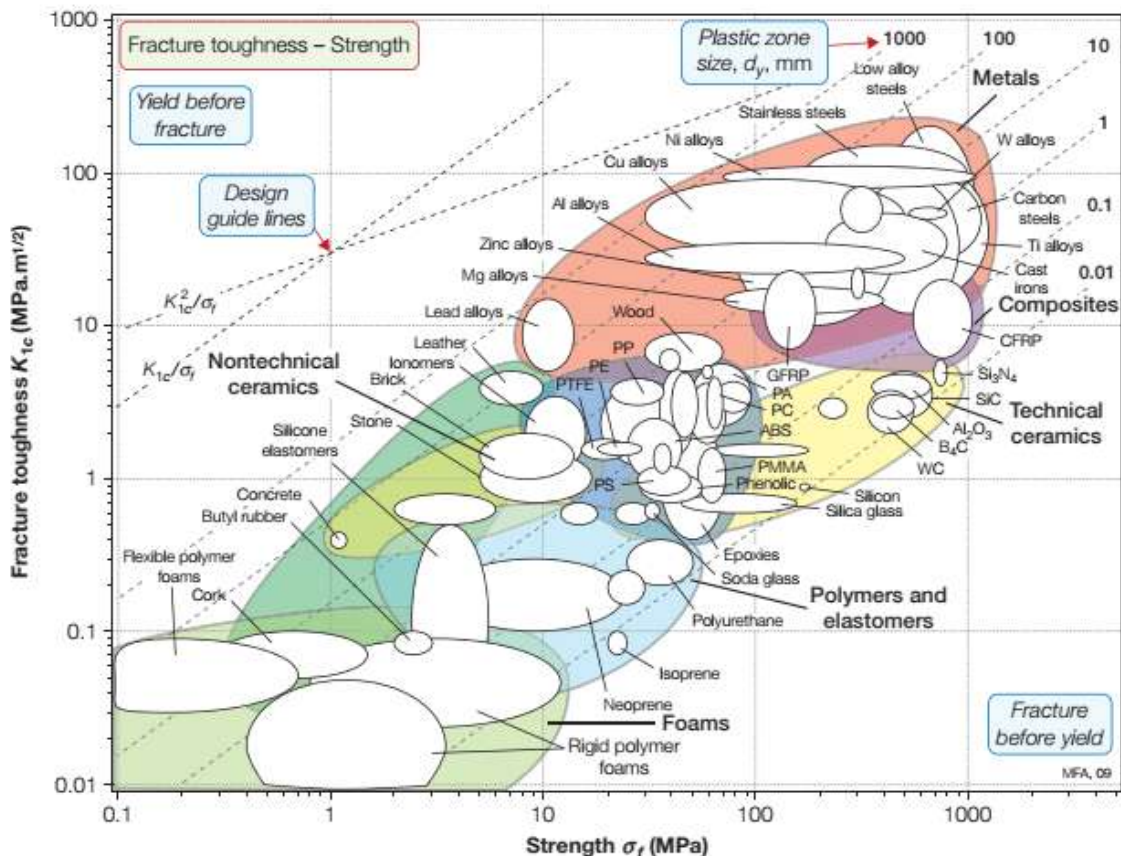


Figure 18: Fracture toughness K_{1c} plotted against strength σ_f . The contours show the value of $K_{1c}^2/\pi\sigma_f^2$ —roughly the diameter d_y of the process zone at a crack tip. The design guide lines are used in selecting materials for damage-tolerant design.

Figure 18, fracture toughness plotted against strength, shows that the size of the zone, d_y (broken lines), varies from atomic dimensions for very brittle ceramics and glasses to almost 1 meter for the most ductile of metals. At a constant zone size, fracture toughness tends to increase with strength, as expected. It is this that causes the data plotted in Figure 18 to be clustered around the diagonal of the chart.

Materials toward the bottom right have high strength and low toughness; they fracture before they yield. Those toward the top left do the opposite: they yield before they fracture.

The diagram has application in selecting materials for the safe design of load-bearing structures.