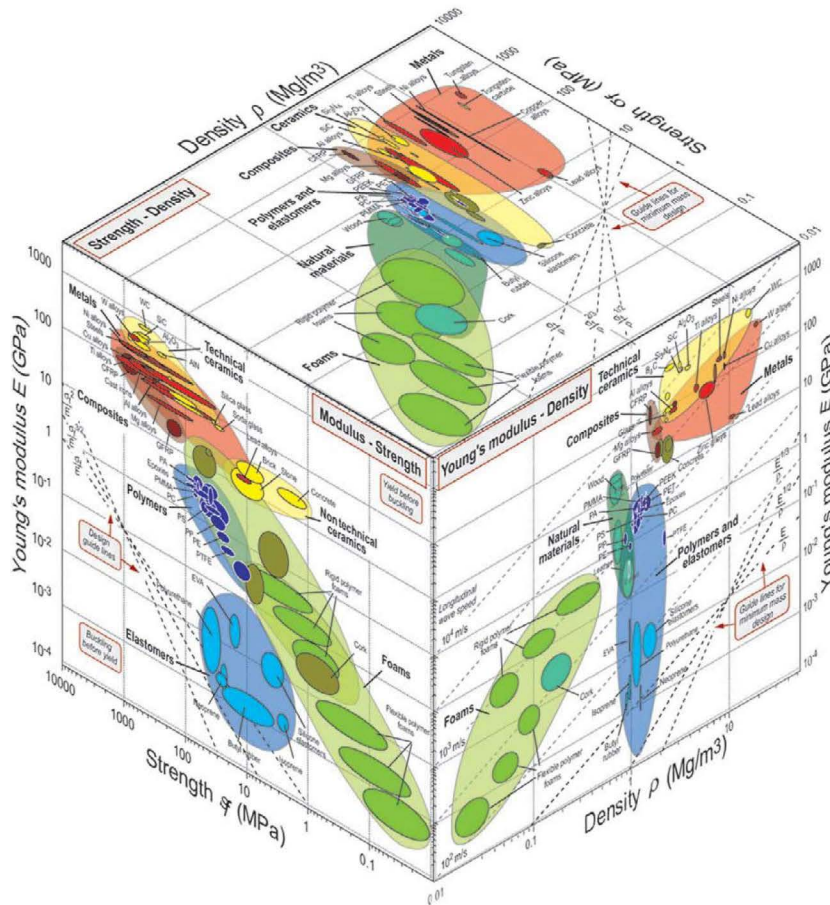


Material Property Charts



A 3-dimensional slice through material property space: the modulus–strength–density slice.

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4.1 INTRODUCTION AND SYNOPSIS

Material properties limit performance. We need a way of surveying them to get a feel for the values that design-limiting properties can have. One property can be displayed as a ranked list or bar chart, but it is seldom that the performance of a component depends on just one property. More often it is a combination of properties that matter: the need for stiffness at low weight, for thermal conduction coupled with corrosion resistance, or for strength combined with toughness, for example. This suggests the idea of plotting one property against another, mapping out the fields in property space occupied by each material class and the subfields occupied by individual materials.

The resulting charts are helpful in many ways. They condense a large body of information into a compact but accessible form; they reveal correlations between material properties that aid in checking and estimating data; and, as examined in later chapters, they become tools for materials selection, for exploring the effect of processing on properties, for demonstrating how shape can enhance structural efficiency, and for suggesting directions for further material development.

The ideas behind materials selection charts are described briefly in Section 4.2. Section 4.3 introduces the charts themselves. It's not necessary to read it all, but it is helpful to persist far enough to be able to read and interpret the charts fluently, and to understand the meaning of the design guide lines that appear in them. If, later, you use a particular chart, you should read the background to it, given here, to be sure of interpreting it correctly.

As explained in the Preface, the charts can be copied and distributed for teaching purposes without infringing the copyright.¹

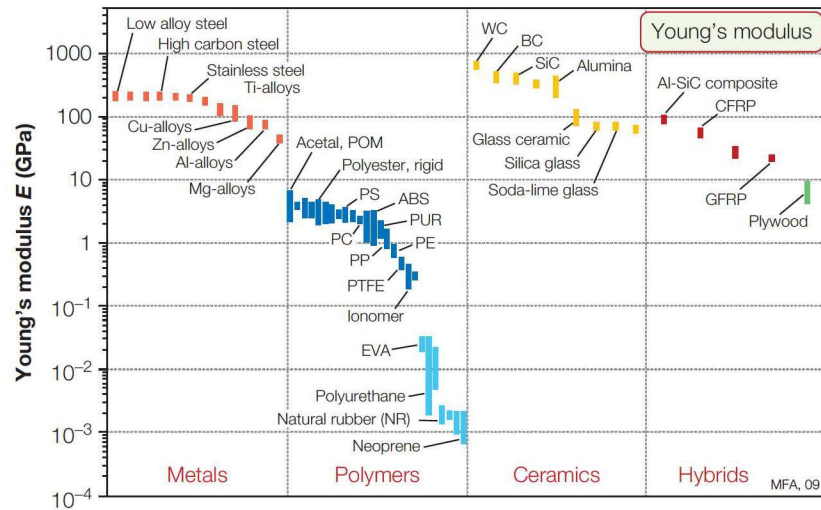
4.2 EXPLORING MATERIAL PROPERTIES

Each property of an engineering material has a characteristic range of values. The span can be large: many properties have values that range over five or more decades. One way of displaying this is as a bar chart like that of Figure 4.1 for Young's modulus. Each bar describes one material; its length shows the range of modulus exhibited by that material in its various forms. The materials are segregated by class. Each class shows a characteristic range: Metals and ceramics have high moduli; polymers have low; hybrids have a wide range, from low to high. The total range is large—it spans a factor of about 10^6 —so logarithmic scales are used to display it.

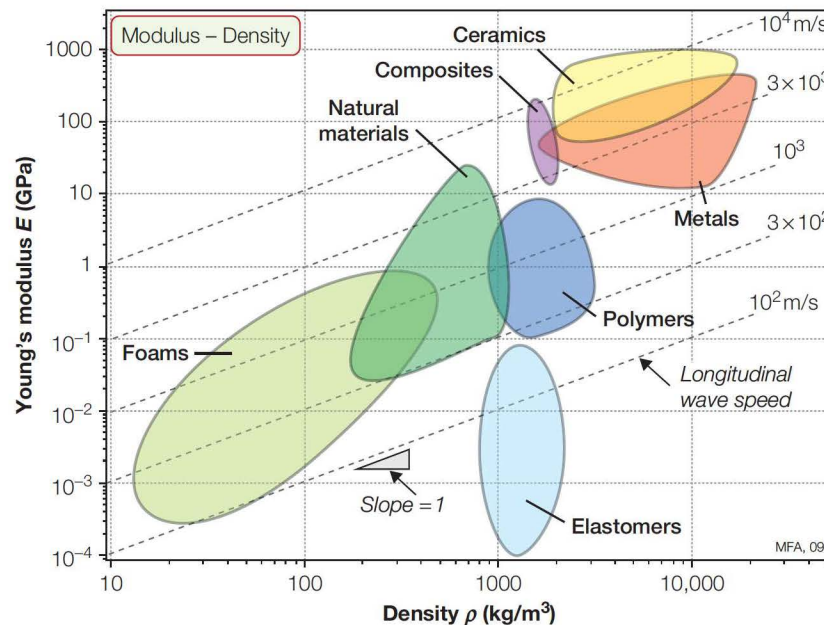
More information is displayed by an alternative plot, illustrated in the schematic of Figure 4.2. Here, one property (the modulus, E , in this case) is plotted against another (the density, ρ). The range of the axes is chosen to include all materials, from the lightest, flimsiest foams to the stiffest, 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. Data for one family can be enclosed in a property envelope—envelopes are shown on this schematic. A real $E - \rho$ chart is shown in Figure 4.3. The family envelopes appear as in the schematic. Within each envelope lie white bubbles enclosing classes and subclasses.

All of this is simple enough—just a helpful way of plotting data. But by choosing the axes and scales appropriately, more can be added. The speed

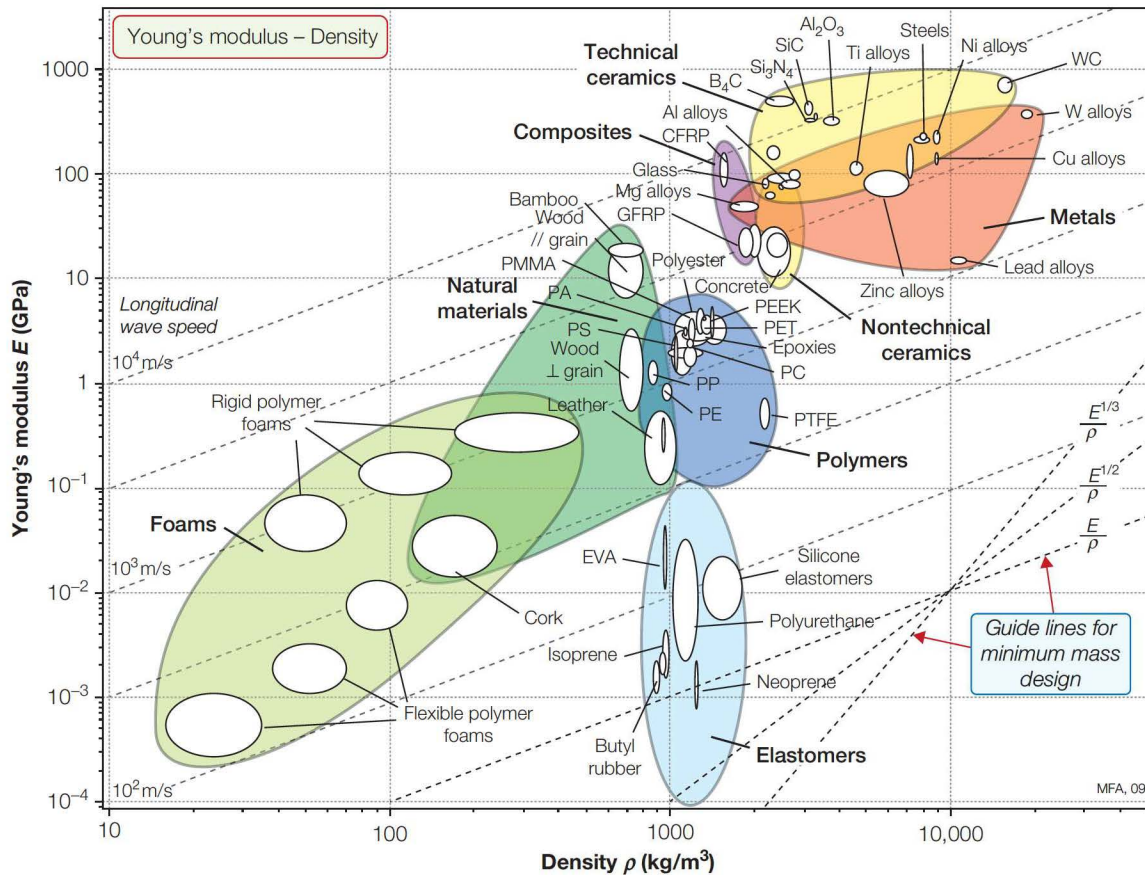
¹ A set of charts can be downloaded from www.grantadesign.com. All charts shown in this chapter were created using Granta Design's CES Edu Materials Selection software. With it you can make charts with any pair (or combination) of properties as axes.

**FIGURE 4.1**

A bar chart showing modulus for families of solids. Each bar shows the range of modulus offered by a material, some of which are labeled.

**FIGURE 4.2**

The idea of a material property chart: Young's modulus E is plotted against the density ρ on log scales. Each material class occupies a characteristic field. The contours show the longitudinal elastic wave speed $v = (E/\rho)^{1/2}$.

**FIGURE 4.3**

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.

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 in Figures 4.2 and 4.3. 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. All the charts allow additional fundamental relationships of this sort to be displayed. And there is more: Design-optimizing parameters called *material indices* also plot as contours on the charts (see Chapter 5).

Among the mechanical and thermal properties, there are 30 or so that are of primary importance, both in characterizing the material and in engineering design. They were listed in Table 3.1 and include density, moduli, strength, hardness, toughness, thermal and electrical conductivities, expansion coefficient, and specific heat. The charts display data for these properties for the families and classes of materials listed in Table 4.1. The list is expanded from the original six of Figure 3.1 by distinguishing *composites* from *foams* and from *natural materials*, and by distinguishing the high-strength *technical ceramics* (e.g., silicon carbide) from the low-strength, *nontechnical ceramics* (e.g., concrete and brick). Within each family, data are plotted for a

Table 4.1 Material Families and Classes

Family	Classes	Short Name
Metals (the metals and alloys of engineering)	Aluminum alloys	Al alloys
	Copper alloys	Cu alloys
	Lead alloys	Lead alloys
	Magnesium alloys	Mg alloys
	Nickel alloys	Ni alloys
	Carbon steels	Steels
	Stainless steels	Stainless steels
	Tin alloys	Tin alloys
	Titanium alloys	Ti alloys
	Tungsten alloys	W alloys
	Lead alloys	Pb alloys
	Zinc alloys	Zn alloys
Ceramics, <i>technical ceramics</i> (fine ceramics capable of load-bearing application)	Alumina	Al ₂ O ₃
	Aluminum nitride	AlN
	Boron carbide	B ₄ C
	Silicon carbide	SiC
	Silicon nitride	Si ₃ N ₄
	Tungsten carbide	WC
Ceramics, <i>nontechnical ceramics</i> (porous ceramics of construction)	Brick	Brick
	Concrete	Concrete
Glasses	Soda-lime glass	Soda-lime glass
	Borosilicate glass	Borosilicate glass
	Silica glass	Silica glass
	Glass ceramic	Glass ceramic

Table 4.1 *continued*

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

representative set of materials, chosen both to span the full range of behavior for the class and to include the most common and most widely used members of it. In this way the envelope for a family encloses data not only for the materials listed in Table 4.1 but for virtually all other members of the family as well.

The charts that follow show a *range* of values for each property of each material. Sometimes the range is narrow: The modulus of copper, for instance, varies by only a few percent about its mean value, influenced by purity, texture, and the like. Sometimes, however, it is wide: The strength of metals can vary by a factor of 100 or more, influenced by composition and the state of work hardening or heat treatment. Crystallinity and degree of cross-linking greatly influence the modulus of polymers. Porosity influences the strength of ceramics. These *structure-sensitive* properties appear as elongated bubbles within the envelopes in the charts.

4.3 THE MATERIAL PROPERTY CHARTS

The modulus–density 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 4.3 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. The same family envelopes appear on all the diagrams: They correspond to the main headings in Table 4.1.

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

$$E = \frac{S}{r_0} \quad (4.1)$$

where r_o is the “atom size” (r_o^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.

But even large atoms ($r_o = 3 \times 10^{-10}\text{ m}$) bonded with the weakest bonds ($S = 0.5\text{ N/m}$) have a modulus of roughly

$$E = \frac{0.5}{3 \times 10^{-10}} \approx 1\text{ GPa} \quad (4.2)$$

This is the *lower limit* for true solids. The chart shows that many materials have moduli that are lower than this: They are either elastomers or foams. 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. More on this in Chapter 11.

The chart shows that the modulus of engineering materials spans seven decades,² from 0.0001 GPa (low-density foams) to 1,000 GPa (diamond). The density spans a factor of 2,000, from less than 0.01 to 20 Mg/m³. Ceramics as a family are very stiff, metals a little less so—but none have a modulus less than 10 GPa. Polymers, by contrast, all cluster between 0.8 and 8 GPa.

The log scales allow more information to be displayed. As explained in the last section, the velocity of elastic waves in a material and the natural vibration frequencies of a component made of it are proportional to $(E/\rho)^{1/2}$. Contours of this quantity are plotted on the chart, labeled with the longitudinal wave speed. The speed varies from less than 50 m/s (soft elastomers) to a little more than 10^4 m/s (stiff ceramics). We note that aluminum and glass, because of their low densities, transmit waves quickly despite their low moduli. One might have expected the wave velocity in foams to be low because of the low modulus, but the low density almost compensates. That in wood, across the grain, is low; but along the grain, it is high—roughly the same as steel—a fact made use of in the design of musical instruments.

² Very-low-density foams and gels (which can be thought of as molecular-scale, fluid-filled foams) can have lower moduli than this. As an example, gelatin (as in Jell-O) has a modulus of about 10^{-5} GPa . Their strengths and fracture toughness, too, can be below the lower limit of the charts.

Surveying material properties

Which class of metallic alloy is the lightest? Which the heaviest? Which the stiffest? Which the least stiff?

Answer

A glance at Figure 4.3 reveals that the lightest class is magnesium alloys and the heaviest is tungsten alloys; tungsten alloys are also the stiffest, and lead alloys are the least stiff.

All the charts that appear in this and subsequent chapters can be used for this fast access to comparisons.

Comparing sound velocities

A metal is needed in which longitudinal waves travel at 300 m/s. Use Figure 4.3 to identify candidates.

Answer

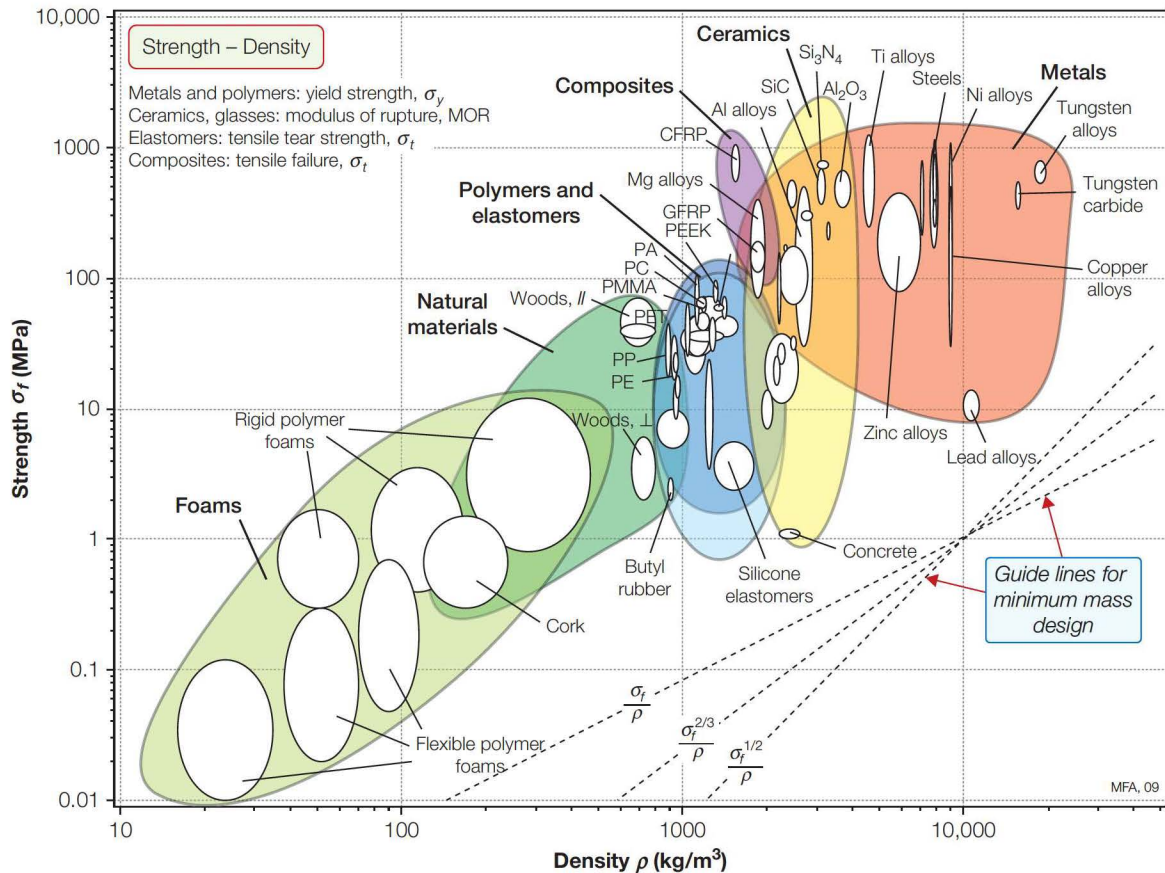
The chart shows that zinc alloys, copper alloys, and tungsten alloys all have a longitudinal wave speed close to 300 m/s.

The chart helps in the common problem of material selection for applications in which mass must be minimized. Guide lines corresponding to three common geometries of loading were shown in Figure 4.3. Their use in selecting materials for stiffness-limited design at minimum weight is described in Chapters 5 and 6.

The strength–density chart

The modulus of a solid is a well-defined quantity with a sharp value. The strength is not. It is shown, plotted against density, ρ , in Figure 4.4.

The word “strength” needs definition (see also Section 3.3). 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). We will use

**FIGURE 4.4**

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.

the symbol σ_f for all of these, despite the different failure mechanisms involved, to allow a first-order comparison.

The range of strength for engineering materials, like the range for the modulus, spans many decades: from less than 0.01 MPa (foams, used in packaging and energy-absorbing systems) to 10^4 MPa (the strength of diamond, exploited in the diamond-anvil press). 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 noncrystalline solids we think instead of the energy associated with the unit step of the flow process as the relative slippage of two segments of a polymer chain, or the shear of a small molecular cluster in a glass network. The strength of noncrystalline solids has the same origin as that underlying the lattice resistance. Thus 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. Materials that fail by fracture do so because the lattice resistance or its amorphous equivalent is so large that atomic separation (fracture) happens first.

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. Their use is described in Chapters 5 and 6.

The modulus–strength chart

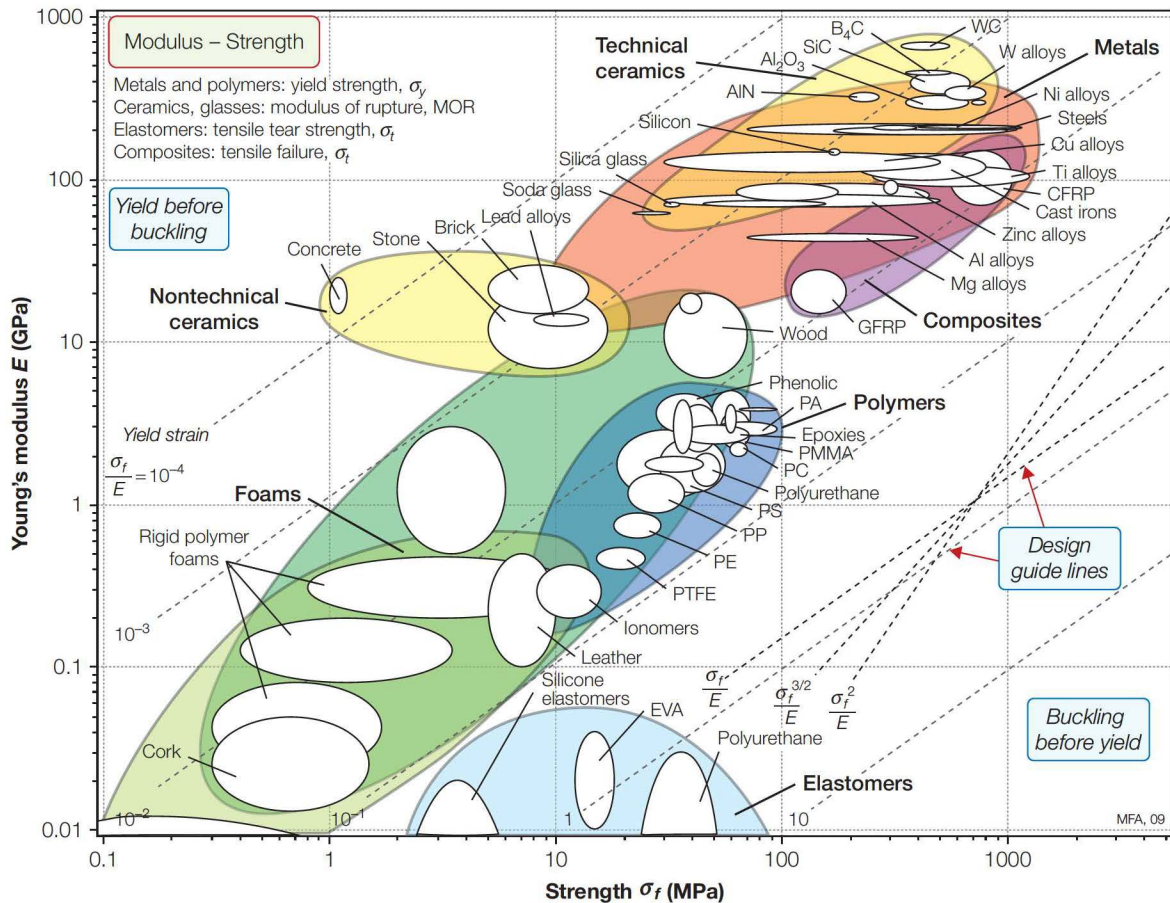
High tensile steel makes good springs. But so does rubber. How is it that two such different materials are both suited to the same task? This and other questions are answered by Figure 4.5, one of the most useful of all the charts. It shows Young's modulus, E , plotted against strength, σ_f . The qualifications for "strength" are the same as before. It means yield strength for metals and

High strength at low weight

Which material has the highest ratio of strength σ_f to density ρ ? Use Figure 4.4 to find out.

Answer

The materials with the largest values of σ_f/ρ are those toward the top left of the figure. The ratio plots as a line of slope 1 on the chart. There is a guide line with this slope among the three at the lower right. The materials with the highest ratio are the ones furthest above such a line. Carbon-fiber-reinforced polymers (CFRPs) stands out as meeting this criterion.

**FIGURE 4.5**

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; their use is described in Chapters 5 and 6.

polymers, flexural strength (modulus of rupture) for ceramics, tear strength for elastomers, and tensile strength for composites and woods; the symbol σ_f is used for them all. 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 distance over which inter atomic forces act is small; a bond is broken if it is stretched to more than about 10% of its original length. So the force F^* needed to break a bond is roughly

$$F^* \approx \frac{Sr_o}{10} \quad (4.3)$$

where S , as before, is the bond stiffness. Then the failure strain of a solid should be roughly

$$\frac{\sigma_f}{E} \approx \frac{F^*}{r_o^2} / \left(\frac{S}{r_o} \right) = \frac{1}{10} \quad (4.4)$$

The chart shows that, for some polymers, the failure strain approaches this value. For most solids it is less, for two reasons.

First, nonlocalized bonds (those in which the cohesive energy derives from the interaction of one atom with large number of others, not just with its nearest neighbors) are not broken when the structure is sheared. The metallic bond, and the ionic bond for certain directions of shear, act in this way. Very pure metals, for example, yield at stresses as low as $E/10,000$, and strengthening mechanisms are needed to make them useful in engineering. The covalent bond is localized, and covalent solids, for this reason, have yield strengths that, at low temperatures, are as high as $E/10$. It is difficult to measure them (though it can sometimes be done by indentation) because of the second reason for weakness: They generally contain defects—concentrators of stress—from which fractures can propagate at stresses well below the “ideal” $E/10$. Elastomers are anomalous (they have strengths of about E) because the modulus does not derive from bond stretching, but from the change in entropy of the tangled molecular chains when the material is deformed.

It has not yet explained how to choose good materials to make springs. This involves the design guide lines shown on the chart, and it will be examined closer in Section 6.7.

Strong solids

Use the strength-density chart of Figure 4.4 to identify three material classes with members having strengths exceeding 1,000 MPa.

Answer

The material classes of steels, titanium alloys, and carbon-fiber composites (CFRPs) all have members with strengths exceeding 1,000 MPa.

High strength at low weight

High-quality mountain bikes are made of materials with particularly high values of the ratio σ_f/ρ , making them strong and light. Which metal class has the highest value of this ratio?

Answer

Figure 4.6 shows that titanium alloys have the highest value.

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, do better on this chart than on the last one.

The chart shown earlier in Figure 4.6 has application in selecting materials for light springs and energy storage devices. We will examine this in Section 6.7.

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_{Ic} , the units of which are $\text{MPa}\cdot\text{m}^{1/2}$. It is plotted against modulus E in Figure 4.7. 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.

At the upper end lie the super-tough materials, all of which show substantial plasticity before they break. For these the values of K_{Ic} are approximate, derived from critical J-integral (J_c) and critical crack-opening displacement (δ_c) measurements, by writing $K_{Ic} = (EJ_c)^{1/2}$, for instance. They are helpful in providing a ranking of materials. The figure shows one reason for the dominance of metals in engineering; they almost all have values of K_{Ic} above 18 $\text{MPa}\cdot\text{m}^{1/2}$, a value often quoted as a minimum for conventional design.

As a general rule, the fracture toughness of polymers is about the same as that of ceramics and glasses. Yet polymers are widely used in engineering structures; ceramics, because they are “brittle,” are treated with much more caution. Figure 4.7 helps resolve this apparent contradiction. Consider first the question of the *necessary condition for fracture*. It is that sufficient external work be done, or elastic energy released, to supply the surface energy, γ per unit area, of the two new surfaces that are created. We write this as

$$G \geq 2\gamma \quad (4.5)$$

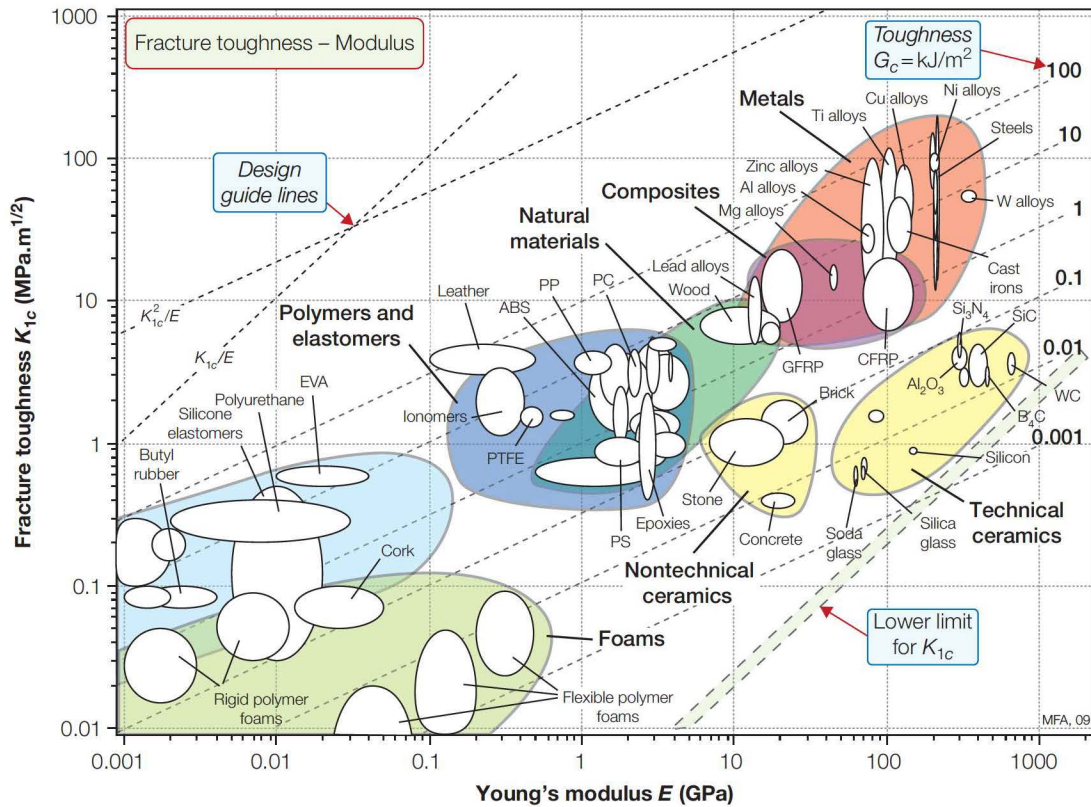


FIGURE 4.7

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} .

where G is the energy release rate. Using the standard relation $K = (EG)^{1/2}$ between G and stress intensity K , we find

$$K \geq (2E\gamma)^{1/2} \quad (4.6)$$

Now the surface energies, γ , of solid materials scale as their moduli; to an adequate approximation $\gamma \approx Er_o/20$, where r_o is the atom size, giving

$$K \geq E\left(\frac{r_o}{20}\right)^{1/2} \quad (4.7)$$

We identify the right-hand side of this equation with a lower-limiting value of K_{1c} when, taking r_o as 2×10^{-10} m,

$$\frac{(K_{1c})_{\min}}{E} = \left(\frac{r_o}{20}\right)^{1/2} \approx 3 \times 10^{-6} \text{ m}^{1/2} \quad (4.8)$$

Comparing materials by toughness

The fracture toughness K_{Ic} of polypropylene (PP) is about $4 \text{ MPa}\cdot\text{m}^{1/2}$. That of aluminum alloys is about 10 times greater. But in deflection-limited design it is toughness G_c that is the more important property. Use Figure 4.7 to compare the two materials by toughness.

Answer

Aluminum and PP have almost exactly the same values of G_c : approximately 10 kJ/m^2 .

This criterion is plotted on the chart as a shaded, diagonal band near the lower right corner. It defines a *lower limit* for K_{Ic} . The fracture toughness cannot be less than this unless some other source of energy such as a chemical reaction, or the release of elastic energy stored in the special dislocation structures caused by fatigue loading, is available, when it is given a new symbol such as $(K_I)_{sc}$ meaning “the critical value of K_I for stress-corrosion cracking” or $(\Delta K_I)_{threshold}$ meaning “the minimum range of K_I for fatigue-crack propagation.” We note that the most brittle ceramics lie close to the threshold. When they fracture, the energy absorbed is only slightly more than the surface energy. When metals, polymers, and composites fracture, the energy absorbed is vastly greater, usually because of plasticity associated with crack propagation.

Plotted on Figure 4.7 are contours of *toughness*, G_c , a measure of the apparent fracture surface energy ($G_c \approx K_{Ic}^2/E$). 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/m^2 . On this scale, ceramics (10^{-3} – 10^{-1} kJ/m^2) are much lower than polymers (10^{-1} – 10 kJ/m^2); this is part of the reason polymers are more widely used in engineering than ceramics. This point is developed further in Section 6.10.

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 . The amount of energy dissipated must scale roughly with the strength of the material within the process zone and with its size, d_y . This size is found by equating the stress field of the crack ($\sigma = K/\sqrt{2\pi r}$) at $r = d_y/2$ to the strength of the material, σ_f , giving

$$d_y = \frac{K_{Ic}^2}{\pi \sigma_f^2} \quad (4.9)$$

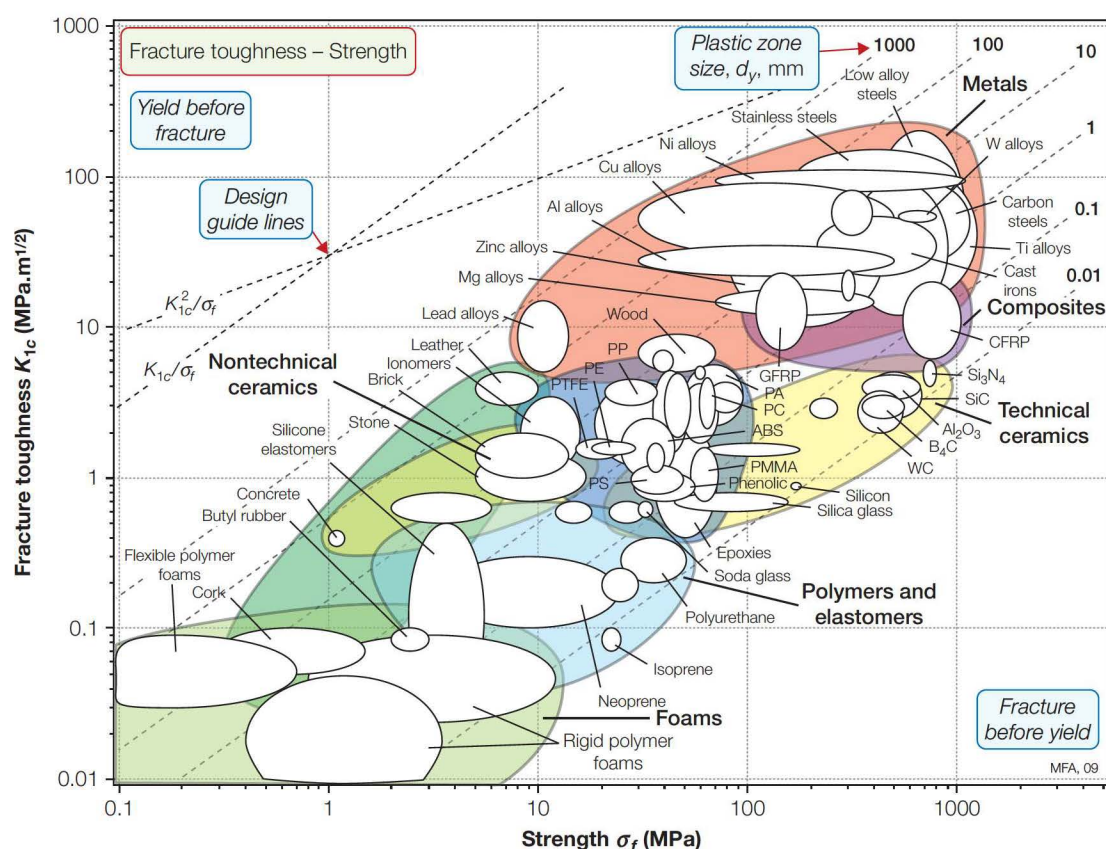


FIGURE 4.8

Fracture toughness K_{Ic} plotted against strength σ_f . The contours show the value of $K_{Ic}^2/\pi\sigma_f^2$ —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 4.8, 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 4.8 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. Examples are given in Sections 6.10 and 6.11.