

Materials Selection in Mechanical Design

Materials Selection in Mechanical Design

Fourth Edition

Michael F. Ashby



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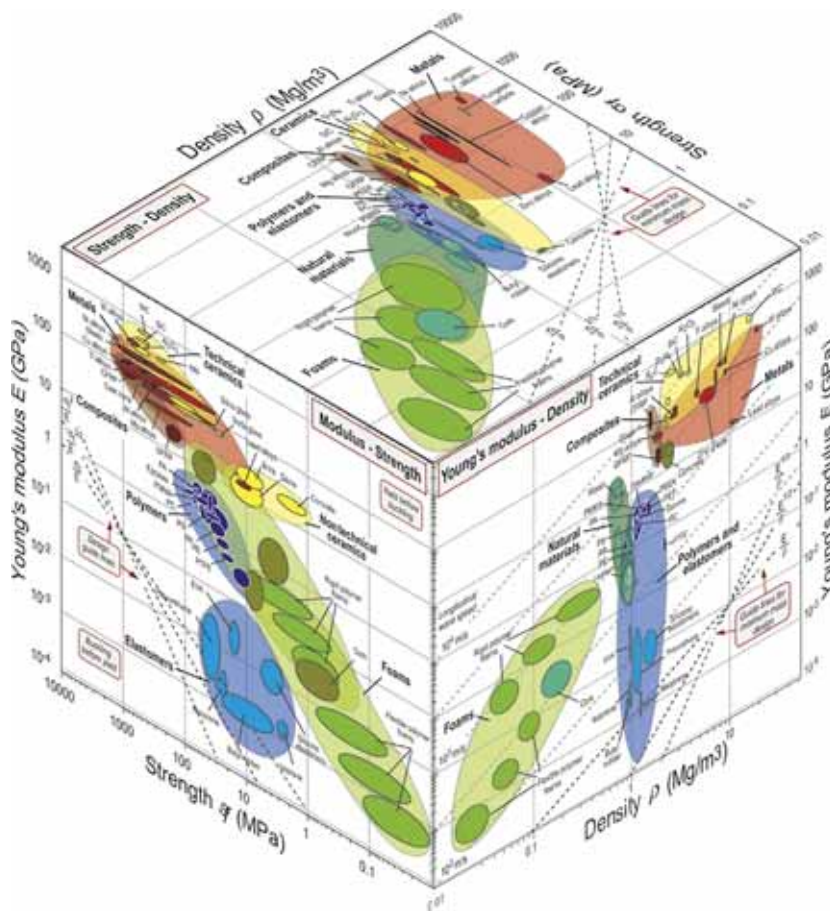
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Material Property Charts



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

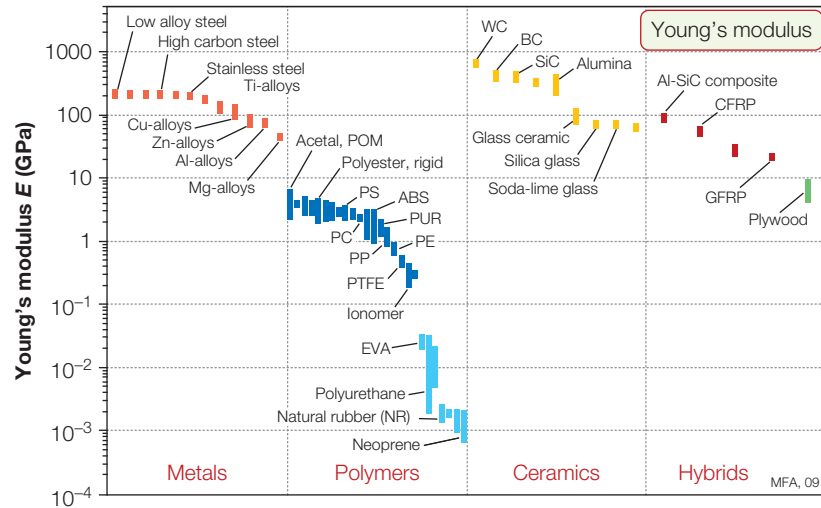
4.2 EXPLORING MATERIAL PROPERTIES

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.

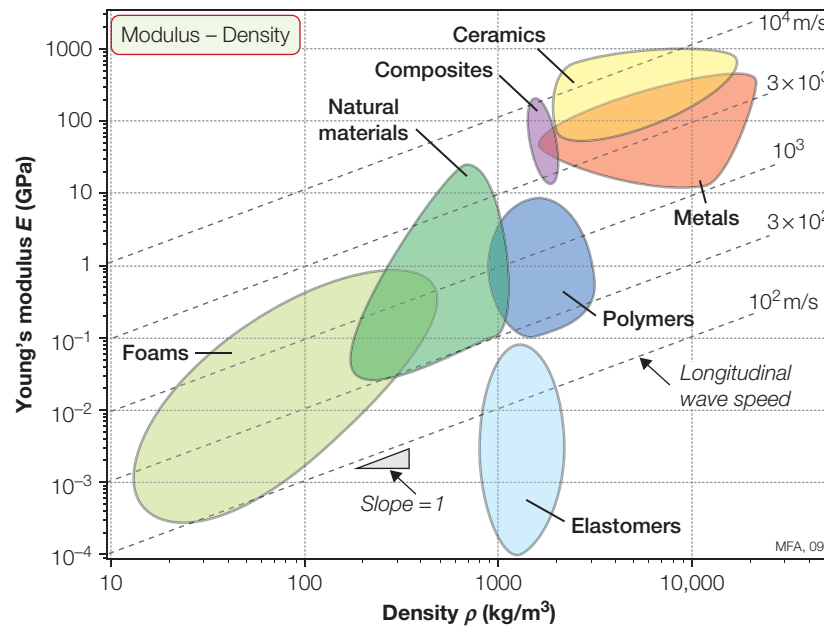
More information is displayed by an alternative plot, illustrated in the schematic of Figure 4.2. Here, one property (the modulus, E , in this case) is plotted against another (the density, ρ). The range of the axes is chosen to include all materials, from the lightest, flimsiest foams to the stiffest, 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

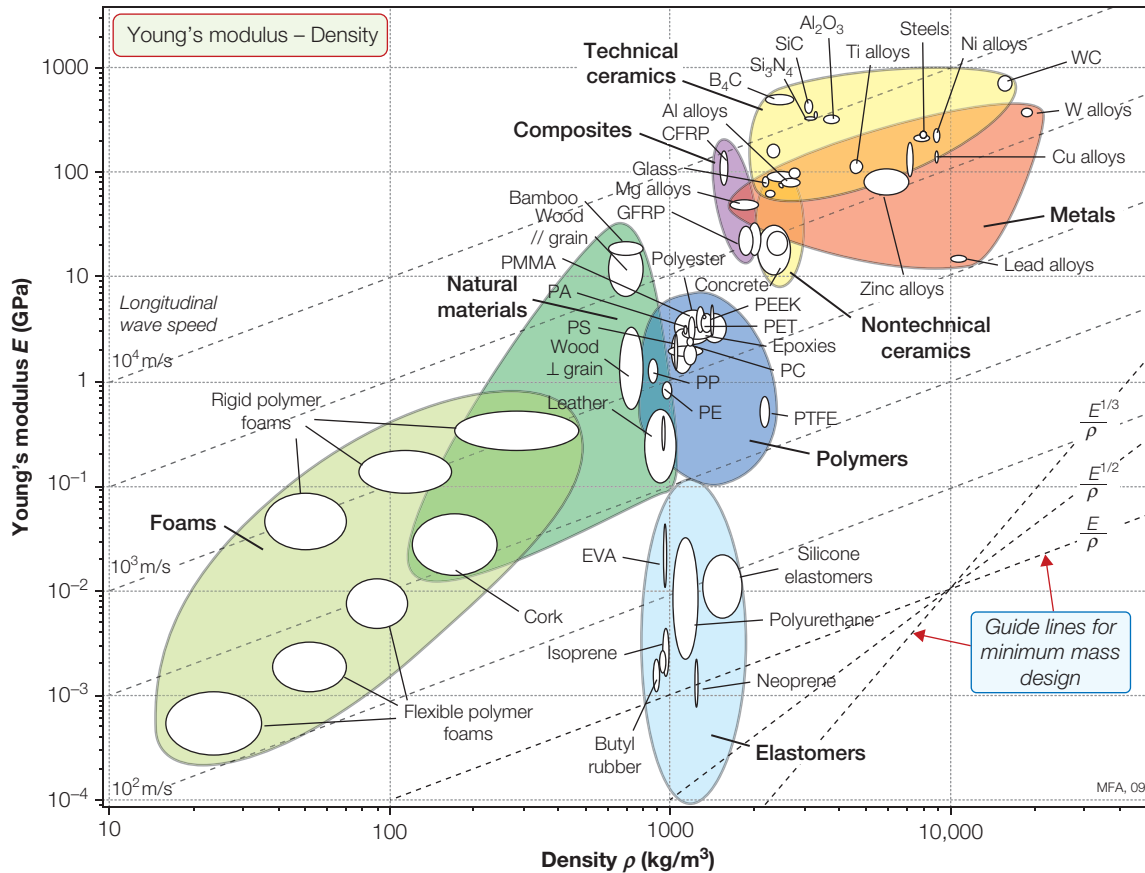
¹ A set of charts can be downloaded from www.grantadesign.com. All charts shown in this chapter were created using Granta Design's CES Edu Materials Selection software. With it you can make charts with any pair (or combination) of properties as axes.

**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
	Epoxy	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

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

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

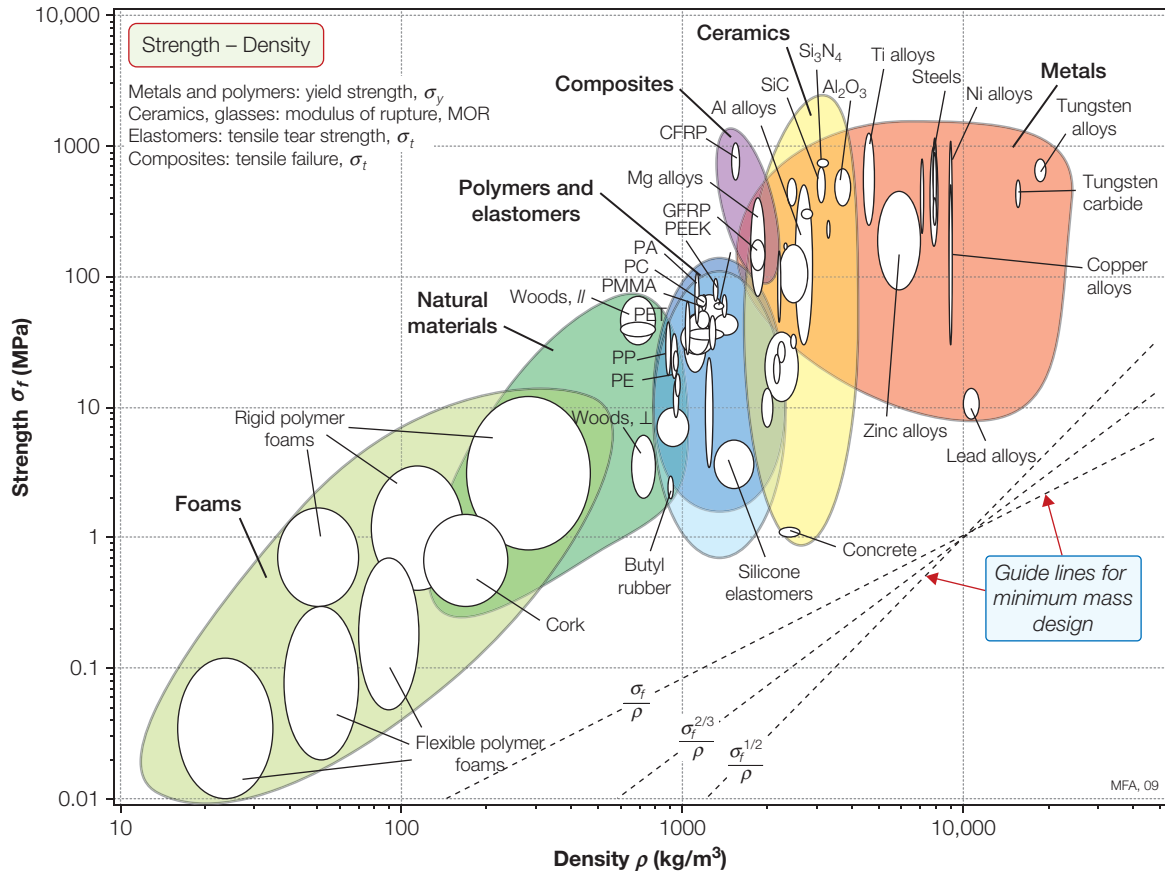
The chart shows that zinc alloys, copper alloys, and tungsten alloys all have a longitudinal wave speed close to 300 m/s.

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

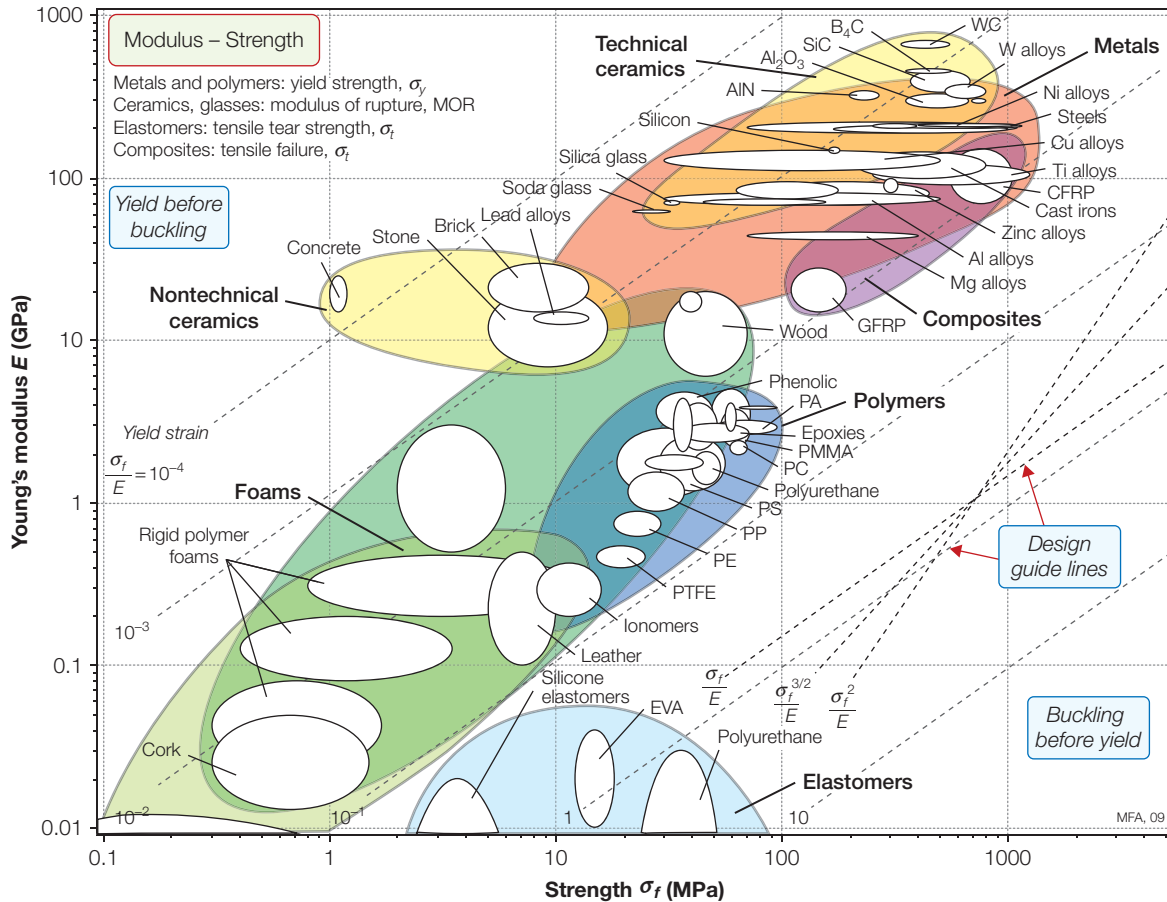
High tensile steel makes good springs. But so does rubber. How is it that two such different materials are both suited to the same task? This and other questions are answered by Figure 4.5, one of the most useful of all the charts. It shows Young’s modulus, E , plotted against strength, σ_f . The qualifications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

The specific stiffness–specific strength chart

Many designs, particularly those for things that move, call for stiffness and strength at minimum weight. To help with this, the data of the previous chart are replotted in Figure 4.6 after dividing, for each material, by the density; it 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.

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

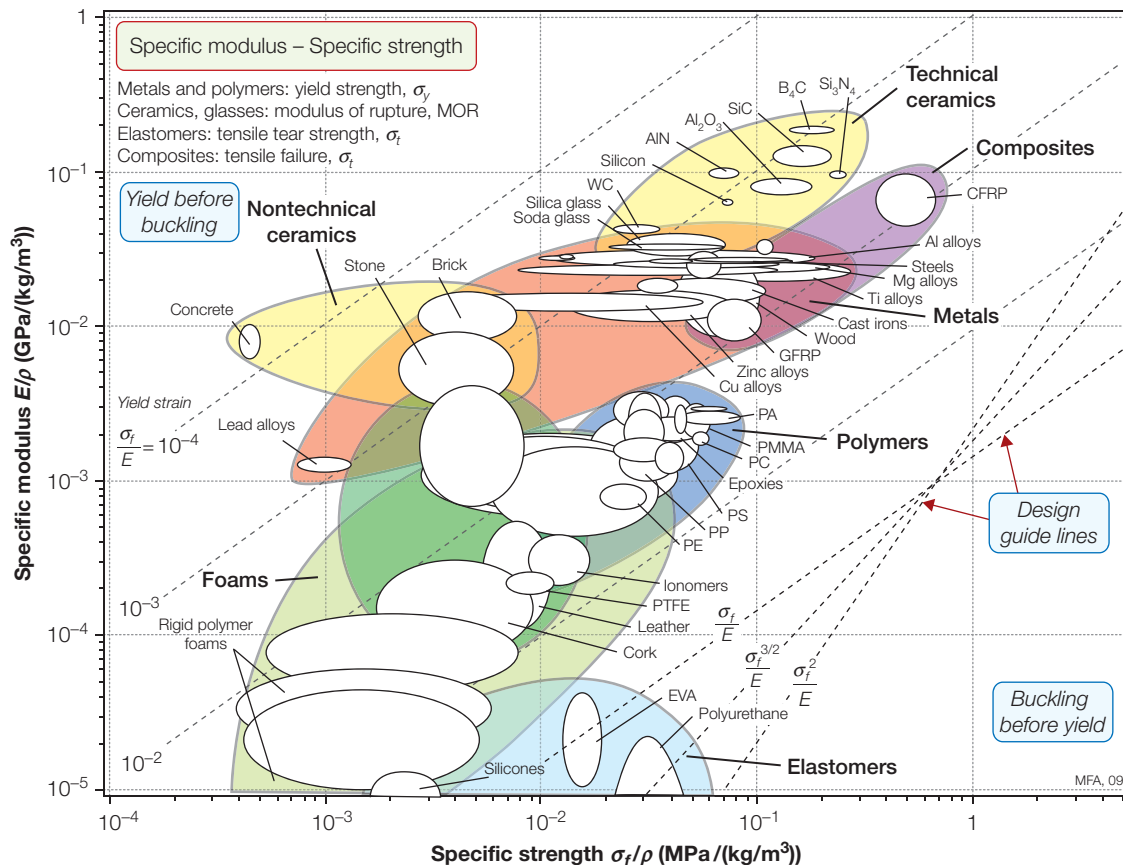


FIGURE 4.6

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.

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

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

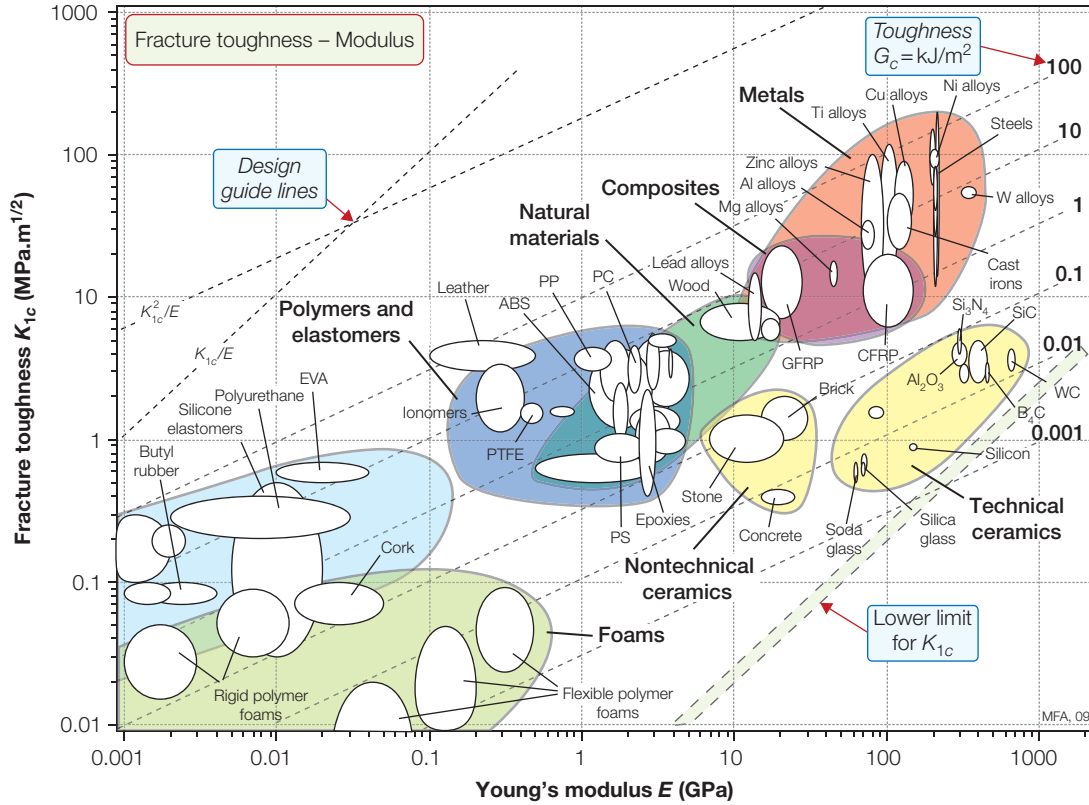


FIGURE 4.7

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 .

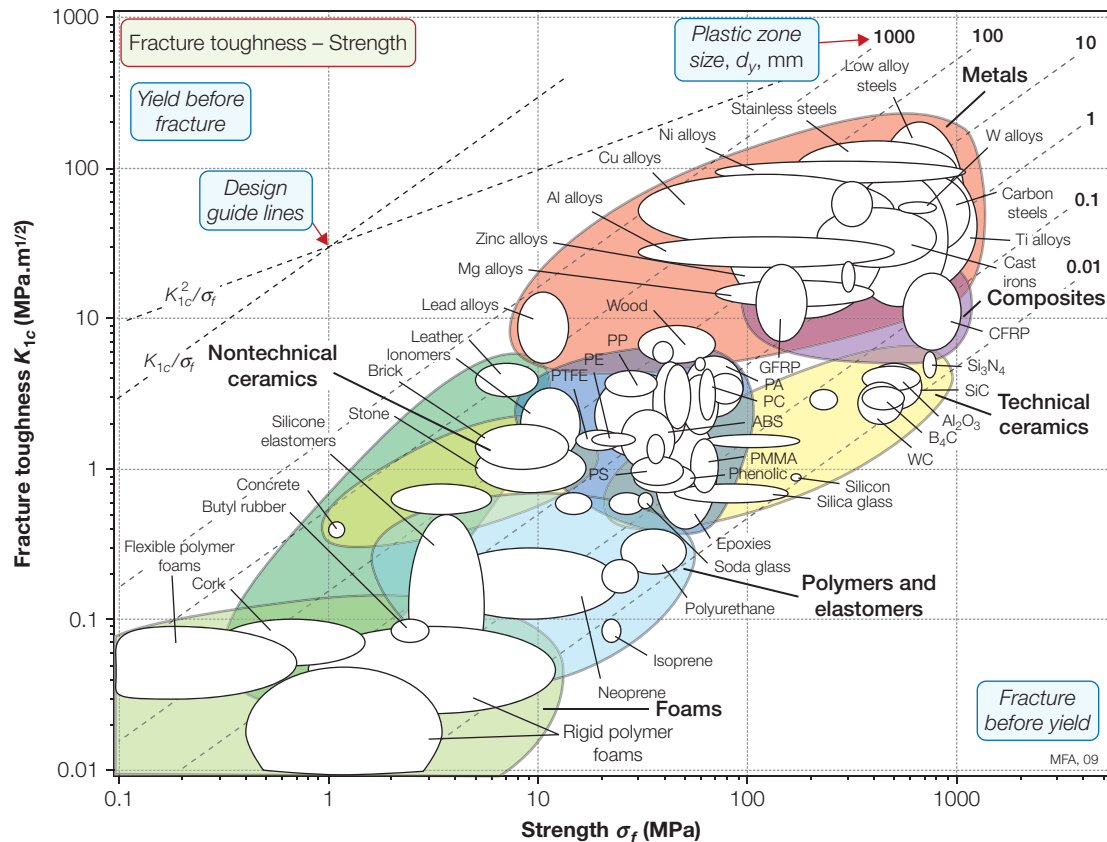
This criterion is plotted on the chart as a shaded, diagonal band near the lower right corner. It defines a *lower limit* for K_{Ic} . The fracture toughness cannot be less than this unless some other source of energy such as a chemical reaction, or the release of elastic energy stored in the special dislocation structures caused by fatigue loading, is available, when it is given a new symbol such as $(K_I)_{scc}$ 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_{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 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.

Valid toughness testing

A valid fracture toughness test requires a sample with dimensions at least 10 times larger than the diameter of the process zone that forms at the crack tip. Use Figure 4.8 to estimate the sample size needed for a valid test on ABS.

Answer

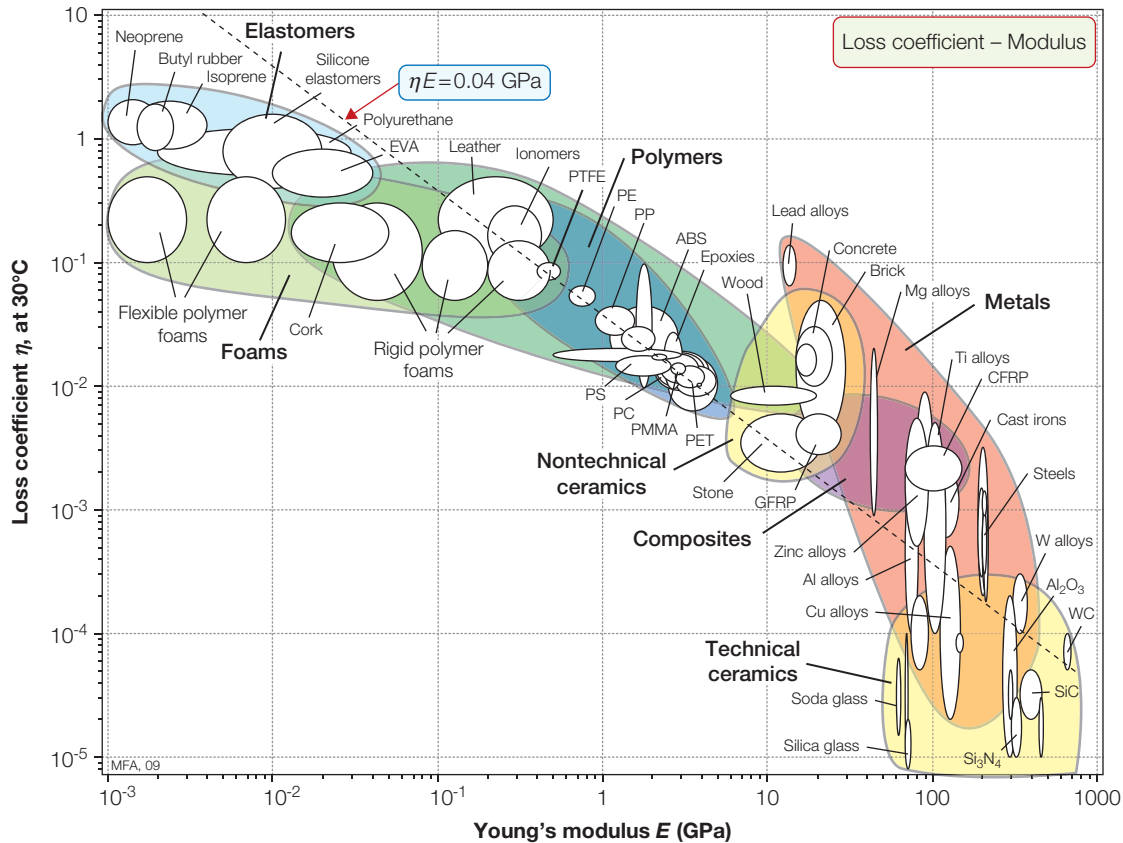
The process zone size for ABS is approximately 1 mm. A valid test requires a sample with dimensions exceeding 10 mm.

The loss coefficient–modulus chart

Bells, traditionally, are made of bronze. They can be made of glass, and they could (if you could afford it) be made of silicon carbide. Metals, glasses, and ceramics all, under the right circumstances, have low intrinsic damping or “internal friction,” an important material property when structures vibrate. Intrinsic damping is measured by the *loss coefficient*, η , which is plotted in Figure 4.9.

There are many mechanisms of intrinsic damping and hysteresis. Some (the “damping” mechanisms) are associated with a process that has a specific time constant; the energy loss is centered about a characteristic frequency. Others, the “hysteresis” mechanisms, are time-independent; they absorb energy at all frequencies. In metals a large part of the loss is hysteretic, caused by dislocation movement: It is high in soft metals like lead and pure aluminum. Heavily alloyed metals like bronze and high-carbon steels have low loss because the solute pins the dislocations; these are the materials for bells. Exceptionally high loss is found in the Mn-Cu alloys, because of a strain-induced martensite transformation, and in magnesium, perhaps because of reversible twinning. The elongated bubbles for metals span the large range made accessible by alloying and work hardening. Engineering ceramics have low damping because of the enormous lattice-resistance pins dislocations that are in place at room temperature.

Porous ceramics, on the other hand, are filled with cracks, the surfaces of which rub, dissipating energy when the material is loaded. The high damping of flake-graphite cast irons has a similar origin. In polymers, chain segments slide against each other when loaded; the relative motion dissipates energy. The ease with which they slide depends on the ratio of the ambient temperature, T , in this case room temperature, to the glass temperature, T_g , of the polymer. When $T/T_g < 1$, the secondary bonds are “frozen,” the modulus is high, and the damping is relatively low. When $T/T_g > 1$, the secondary bonds have melted, allowing easy chain slippage; the modulus is

**FIGURE 4.9**

The loss coefficient η plotted against Young's modulus E . The guide line corresponds to the condition $\eta = CE$.

low, and the damping is high. This accounts for the obvious inverse dependence of η on E for polymers in Figure 4.9; indeed, to a first approximation,

$$\eta = \frac{4 \times 10^{-2}}{E} \quad (4.10)$$

(with E in GPa) for polymers, woods, and polymer-matrix composites.

Vibration damping

A metal is sought for mountings to damp vibration of a small machine tool. Use Figure 4.9 to find the metal with the greatest value of the damping coefficient η to use for the mountings.

Answer

Lead or lead alloys are the best choice.

Vibrational heating

A centrifuge rotating at $f = 5,000$ rpm is attached to a PTFE (Teflon) mounting. Poor balancing causes the centrifuge to vibrate, loading the PTFE up to a peak stress of $\sigma_{\max} = 8$ MPa on each cycle. If a centrifuge run lasts 10 minutes and no heat is lost from the PTFE, by how much will its temperature rise? Take the volume-specific heat for PTFE (which can be read from Figure 4.11) to be $\rho C_p = 2 \times 10^6$ J/m³.K, and retrieve the other material properties you need from Figure 4.9.

Answer

Figure 4.9 shows that the modulus of PTFE is $E = 0.4$ GPa and its loss coefficient is $\eta = 0.08$. The peak elastic energy stored in the PTFE in any one cycle is

$$U_{\max} = \frac{\sigma_{\max}^2}{2E} = 10^4 \text{ J/m}^3$$

of which $\Delta U = 2\pi\eta U_{\max}$ (Equation (3.10)) is lost on each cycle. Thus the energy dumped into the PTFE over 5 minutes is

$$U_{10\text{mins}} = 2\pi\eta U_{\max}(5f) = 2.52 \times 10^8 \text{ J/m}^3$$

Dividing this by the volume-specific heat of PTFE reveals a temperature rise of 126 °C. It will be necessary to ensure that heat can be conducted away from the mount to prevent it overheating.

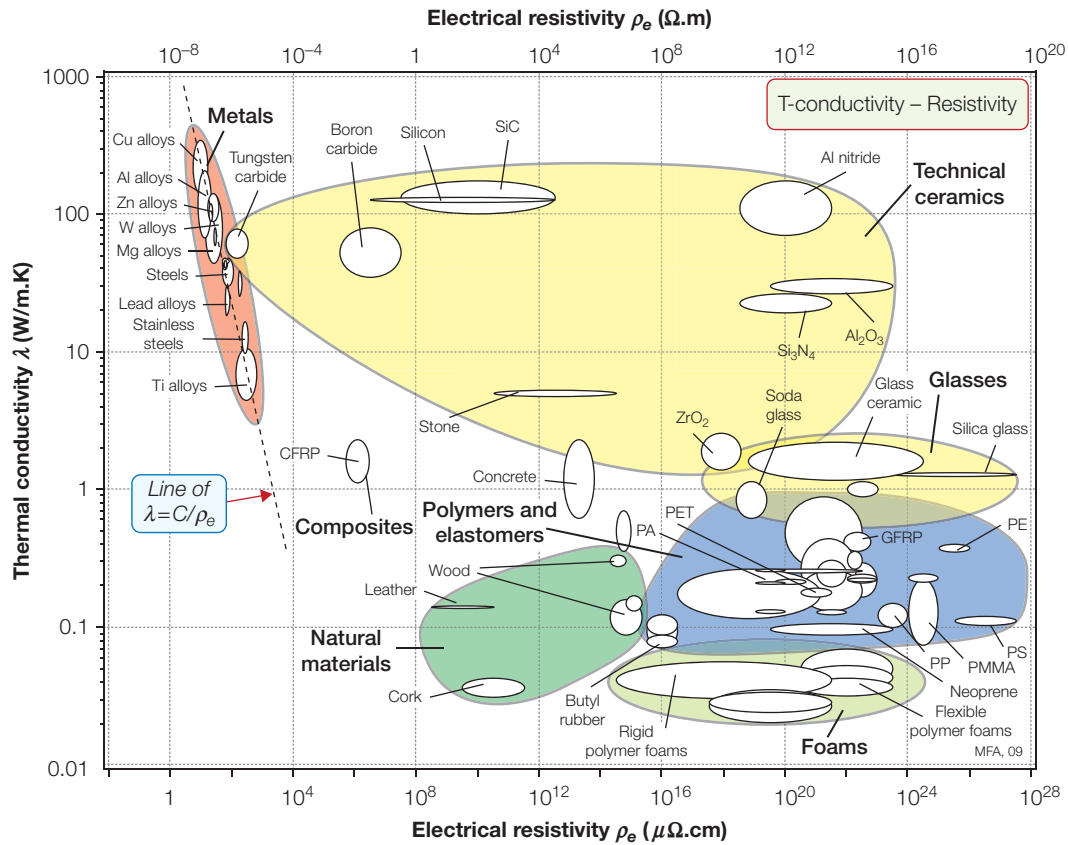
The thermal conductivity–electrical resistivity chart

The material property governing the flow of heat through a material at steady state is the *thermal conductivity*, λ (units: W/m.K). (See Figure 4.10.) The valence electrons in metals are “free,” moving like a gas within the lattice of the metal. Each electron carries a kinetic energy, $\frac{3}{2}kT$, where k is Boltzmann’s constant. It is the transmission of this energy, via collisions, that conducts heat in metals. The thermal conductivity is described by

$$\lambda = \frac{1}{3} C_e \bar{c} \ell \quad (4.11)$$

where C_e is the electron specific heat per unit volume, $\bar{c}$ is the electron velocity (2×10^5 m/s), and ℓ is the electron mean-free path, typically 10^{-7} m in pure metals. In heavily alloyed solid solutions (stainless steels, nickel-based superalloys, and titanium alloys) the foreign atoms scatter electrons, reducing the mean free path to atomic dimensions ($\approx 10^{-10}$ m), much reducing λ .

These same electrons, when in a potential gradient, drift through the lattice, giving electrical conduction. The electrical conductivity, κ , is measured here

**FIGURE 4.10**

Thermal conductivity λ plotted against electrical resistivity ρ_e . For metals the two are related.

by its reciprocal, the *resistivity* ρ_e (SI units: $\Omega.m$, units of convenience $\mu\Omega.cm$). The range is enormous: a factor of 10^{28} , far larger than that of any other property. As with heat, the conduction of electricity in metals is proportional to the density of carriers, the electrons, and their mean-free path, leading to the Wiedemann-Franz relation

$$\lambda \propto \kappa = \frac{1}{\rho_e} \quad (4.12)$$

The quantities λ and ρ_e are the axes of Figure 4.10. Data for metals appear at the top left. The broken line shows that the Wiedemann-Franz relation is well obeyed.

But what about the rest of the chart? Electrons do not contribute to thermal conduction in ceramics and polymers. Heat is carried instead by

phonons—lattice vibrations of short wavelength. They are scattered by each other and by impurities, lattice defects, and surfaces; it is these that determine the phonon mean-free path, ℓ . The conductivity is still given by equation (4.11), which we write as

$$\lambda = \frac{1}{3} \rho C_p \bar{c} \ell \quad (4.13)$$

but now $\bar{c}$ is the elastic wave speed (around 10^3 m/s—see Figure 4.3), ρ is the density, and C_p is the *specific heat per unit mass* (units: J/kg.K). If the crystal is particularly perfect and the temperature is well below the Debye temperature, as in diamond at room temperature, the phonon conductivity is high: It is for this reason that single crystal silicon carbide and aluminum nitride have thermal conductivities almost as high as copper.

The low conductivity of glass is caused by its irregular amorphous structure; the characteristic length of the molecular linkages (about 10^{-9} m) determines the mean free path. Polymers have low conductivities because the elastic wave speed $\bar{c}$ is low (see Figure 4.3), and the mean free path in the disordered structure is small. Highly porous materials like firebrick, cork, and foams show the lowest thermal conductivities, limited by the thermal conductivity of the gas in their cells.

Graphite and many intermetallic compounds such as C and B_4C , like metals, have free electrons, but the number of carriers is smaller and the resistivity is higher than in metals. Defects such as vacancies and impurity atoms in ionic solids create positive ions that require balancing electrons. These can jump from ion to ion, conducting charge, but slowly because the carrier density is low. Covalent solids and most polymers have no mobile electrons and are insulators ($\rho_e > 10^{12} \mu\Omega\cdot\text{cm}$)—they lie on the right side of Figure 4.10.

Under a sufficiently high potential gradient, anything will conduct. The gradient tears electrons free from even the most possessive atoms, accelerating them into collision with nearby atoms, knocking out more electrons and creating a cascade. The critical gradient is the *breakdown potential*, V_b (units: MV/m), defined in Chapter 3.

Conducting heat but not electricity

Which materials are both good thermal conductors and good electrical insulators (an unusual combination)? Use Figure 4.10 to find out.

Answer

The chart identifies aluminum nitride, alumina, and silicon nitride as having these properties. They are the ones at the top right.

The thermal conductivity–thermal diffusivity chart

Thermal conductivity, as we have said, governs the flow of heat through a material at steady state. The property governing transient heat flow is the *thermal diffusivity*, a (units: m^2/s). The two are related by

$$a = \frac{\lambda}{\rho C_p} \quad (4.14)$$

where ρ in kg/m^3 is the density. The quantity ρC_p is the *volumetric specific heat* (units: $\text{J}/\text{m}^3\cdot\text{K}$). Figure 4.11 relates thermal conductivity, diffusivity, and volumetric specific heat, at room temperature.

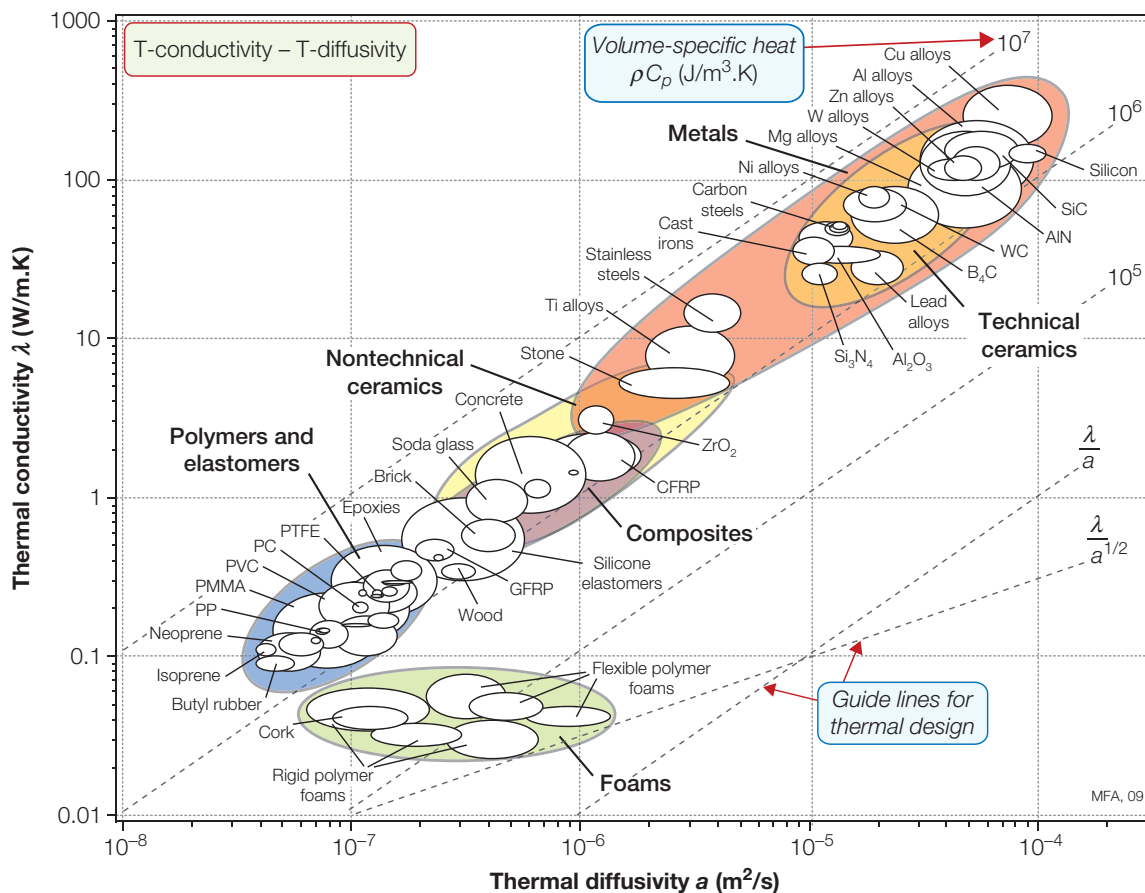


FIGURE 4.11

Thermal conductivity λ plotted against thermal diffusivity a . The contours show the volume-specific heat ρC_p . All three properties vary with temperature; the data here are for room temperature.

Thermal buffers

A good way to protect equipment from sudden temperature change is to encase it in a material with a very low thermal diffusivity, because an external temperature change then takes a long time to reach the inside. Use Figure 4.11 to identify materials that could be good for this.

Answer

The chart identifies isoprene, neoprene, and butyl rubber as potential candidates.

The data span almost five decades in λ and a . Solid materials are strung out along the line³

$$\rho C_p \approx 3 \times 10^6 \text{ J/m}^3 \cdot \text{K} \quad (4.15)$$

As a general rule, then,

$$\lambda = 3 \times 10^6 a \quad (4.16)$$

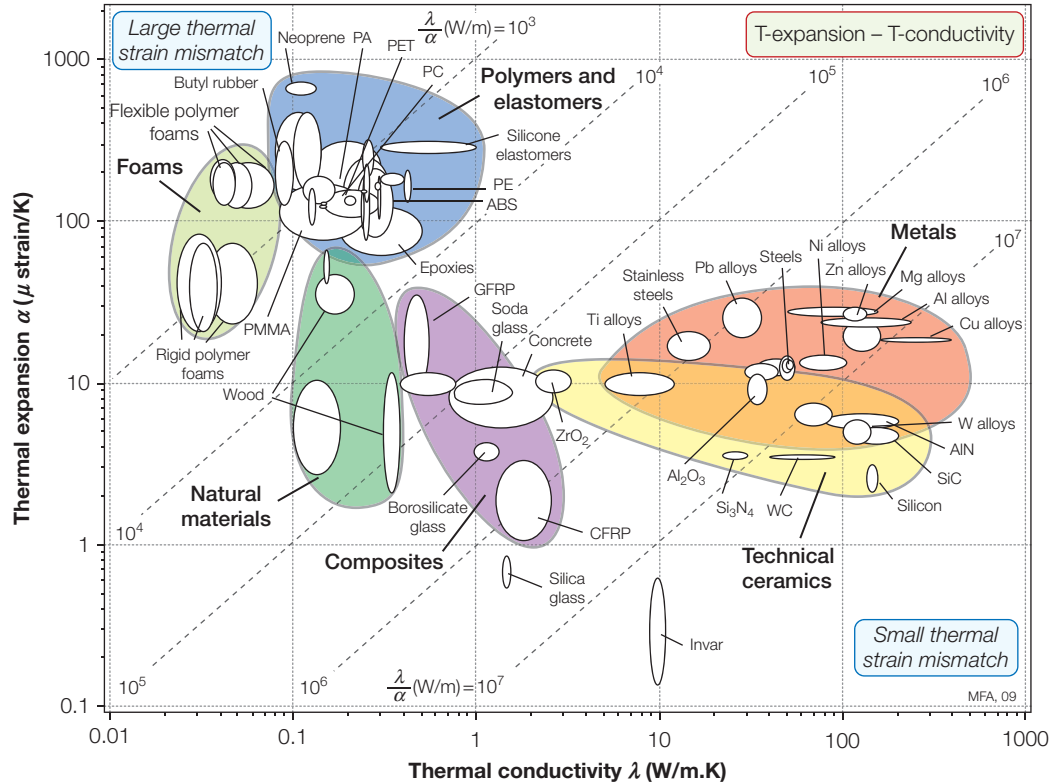
(λ in W/m.K and a in m²/s). Some materials deviate from this rule because they have lower than average volumetric specific heat. The largest deviations are shown by porous solids: foams, low-density firebrick, woods, and the like. Their low density means that they contain fewer atoms per unit volume and, averaged over the volume of the structure, ρC_p is low. The result is that, although foams have low thermal *conductivities* and are widely used for insulation, their thermal *diffusivities* are not necessarily low: They may not transmit much heat, but they reach a steady state quickly. This is important in design, a point illustrated by the case study in Section 6.13.

The thermal expansion–thermal conductivity chart

Almost all solids expand on heating (Figure 4.12). The bond between a pair of atoms behaves like a linear elastic spring when the relative displacement of the atoms is small, but when it is large the spring is nonlinear. Most bonds become stiffer when the atoms are pushed together and less stiff when they are pulled apart. Such bonds are anharmonic. The thermal vibrations of atoms, even at room temperature, involve large displacements; as

³ This can be understood by noting that a solid containing N atoms has $3N$ vibrational modes. Each (in the classical approximation) absorbs thermal energy kT at the absolute temperature T , and the vibrational specific heat is $C_p \approx C_v = 3Nk$ (J/K) where k is Boltzmann's constant (1.34×10^{-23} J/K). The volume per atom Ω for almost all solids lies within a factor of two of 1.4×10^{-29} m³; thus the volume of N atoms is $(N\Omega)$ m³. The volume-specific heat is then (as the chart shows):

$$\rho C_v \approx 3Nk/N\Omega = \frac{3k}{\Omega} = 3 \times 10^6 \text{ J/m}^3 \cdot \text{K}$$

**FIGURE 4.12**

The linear expansion coefficient α plotted against the thermal conductivity λ . The contours show the thermal distortion parameter λ/α . An extra material, the nickel alloy Invar, has been added to the chart; it is noted for its exceptionally low expansion at and near room temperature, useful in designing precision equipment that must not distort if the temperature changes.

the temperature is raised, the anharmonicity of the bond pushes the atoms apart, increasing their mean spacing. The effect is measured by the linear expansion coefficient

$$\alpha = \frac{1}{\ell} \frac{d\ell}{dT} \quad (4.17)$$

where ℓ is a linear dimension of the body.

The expansion coefficient is plotted against the thermal conductivity in Figure 4.12. It shows that polymers have large values of α , roughly 10 times greater than those of metals and almost 100 times greater than those of ceramics. This is because the Van der Waals bonds of the polymer are very anharmonic. Diamond, silicon, and silica glass (SiO_2) have covalent bonds that have low anharmonicity (that is, they are almost linear elastic even at

Thermal actuators

An actuator uses thermal expansion of its active element to generate the actuating force. Use Figure 4.12 to identify the material with the largest expansion coefficient.

Answer

Neoprene, at the upper left of the chart, has a larger value of expansion coefficient than any other on the chart.

large strains), giving them low expansion coefficients. Composites, even though they have polymer matrices, can have low values of α because the reinforcing fibers, particularly carbon, expand very little.

The chart shows contours of λ/α , a quantity important in designing against thermal distortion. An extra material, Invar (a nickel alloy), has been added to the chart because of its uniquely low expansion coefficient at and near room temperature, a consequence of a trade-off between normal expansion and a contraction associated with a magnetic transformation. An application that uses the chart is developed in Chapter 6, Section 6.16.

The thermal expansion–modulus chart

Thermal stress is the stress that appears in a body when it is heated or cooled but prevented from expanding or contracting. It depends on the expansion coefficient, α , of the material and on its modulus, E . A standard development of the theory of thermal expansion leads to the relationship

$$\alpha = \frac{\gamma_G \rho C_p}{3E} \quad (4.18)$$

where γ_G is Gruneisen's constant. It has values between 0.4 and 4, but for most solids it is near 1. Since ρC_p is almost constant (see Equation (4.15)), the equation tells us that α is proportional to $1/E$. Figure 4.13 shows that this is broadly so. Ceramics, with the highest moduli, have the lowest coefficients of expansion; elastomers with the lowest moduli expand the most. Some materials with a low coordination number (silica and some diamond-cubic or zinc-blend structured materials) can absorb energy preferentially in transverse modes, leading to very small or negative values of γ_G and a low expansion coefficient (silica, SiO_2 , is an example). Others, like Invar, contract as they lose their ferromagnetism when heated through the Curie temperature; over a narrow range of temperature, they too show near-zero expansion, useful in the manufacture of precision equipment and in glass-metal seals.

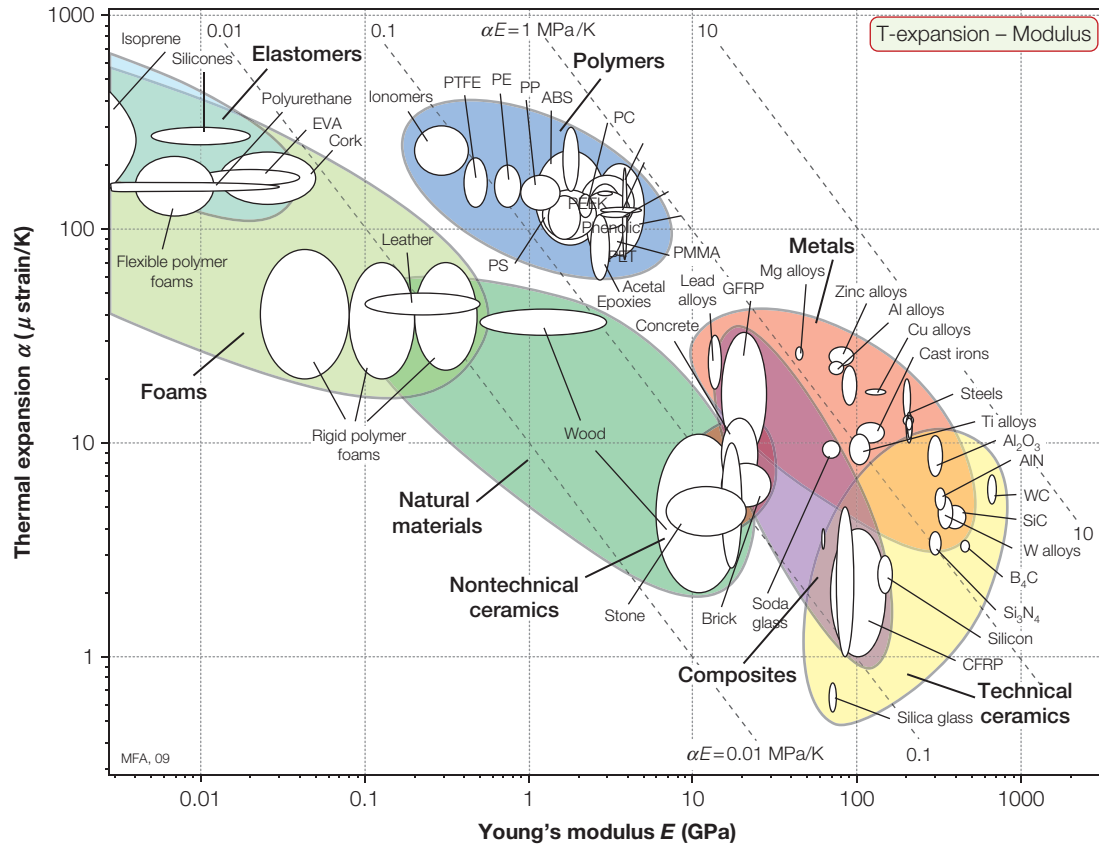


FIGURE 4.13

The linear expansion coefficient α plotted against Young's modulus E . The contours show the thermal stress created by a temperature change of 1°C if the sample is axially constrained. A correction factor C is applied for biaxial or triaxial constraint (see text).

One more useful fact. The moduli of materials scale approximately with their melting point, T_m :

$$E \approx \frac{100 k T_m}{\Omega} \quad (4.19)$$

where k is Boltzmann's constant and Ω is the volume per atom in the structure. Substituting this and equation (4.15) for ρC_p into equation (4.18) for α gives

$$\alpha = \frac{\gamma_G}{100 T_m} \quad (4.20)$$

—the expansion coefficient varies inversely with the melting point. Equivalently, the thermal strain for all solids, just before they melt, depends only

Thermal stress

Approximately what stress will appear in a rod of steel, rigidly clamped at its ends, if its temperature is changed by 100°C? Use Figure 4.13 to find out.

Answer

The figure shows that, for steel, $\alpha E \approx 3 \text{ MPa/K}$. Thus, a temperature change of 100°C will create a stress of approximately 300 MPa.

on γ_C , and this is roughly a constant at about 1%. Equations (4.18), (4.19), and (4.20) are examples of property correlations, useful for estimating and checking material properties (Appendix A, Section A.12).

Whenever the thermal expansion or contraction of a body is prevented, thermal stresses appear; if large enough, these stresses cause yielding, fracture, or elastic collapse (buckling). It is common to distinguish between thermal stress caused by external constraint (a rod rigidly clamped at both ends, for example) and that which appears without external constraint because of temperature gradients in the body. All scale as the quantity αE , shown as a set of diagonal contours in Figure 4.13. More precisely, the stress $\Delta\sigma$ produced by a temperature change of 1°C in a constrained system, or the stress per °C caused by a sudden change of surface temperature in one that is not constrained, is given by

$$C \Delta\sigma = \alpha E \quad (4.21)$$

where $C = 1$ for axial constraint, $(1 - \nu)$ for biaxial constraint or normal quenching, and $(1 - 2\nu)$ for triaxial constraint, where ν is Poisson's ratio. These stresses are large: typically 1 MPa/K. They can cause a material to yield, crack, spall, or buckle when it is suddenly heated or cooled.

The maximum service temperature chart

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 oxidize 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 of these reasons, it is unsafe to use a material is called its *maximum service temperature* $T_{\max}$. Figure 4.14 show this plotted as a bar chart.

The chart gives a birds-eye view of the regimes of temperature in which each material class is usable. Note that few polymers can be used above 200°C, few metals above 800°C, and only ceramics offer strength above 1,500°C.

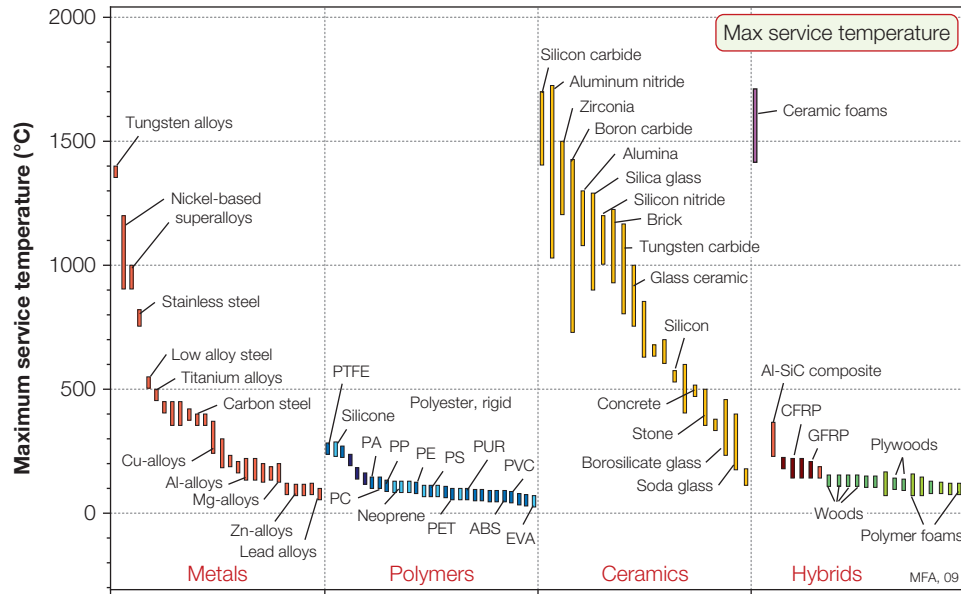


FIGURE 4.14

The maximum service temperature—the temperature above which a material becomes unusable.

Friction and wear

God, it is said, created materials but the devil made surfaces. Surfaces are the source of many problems. When surfaces touch and slide, there is friction; where there is friction, there is wear. Tribologists—those who study friction and wear—are fond of citing the enormous cost, through lost energy and worn equipment, for which these two phenomena are responsible. It is certainly true that, if friction could be eliminated, the efficiency of engines, gear boxes, drive trains, and the like, would increase. If wear could be eradicated, they would also last longer. But before accepting this negative image, one should remember that without wear pencils would not write on paper or chalk on blackboards; without friction, one would slither off the slightest incline.

Use temperature for stainless steel

Stainless steel is proposed for use as part of a structure operating at 500°C. Is it safe to do so?

Answer

Figure 4.14 shows that the maximum use temperature for stainless steel is in the range 700 to 1,100°C. Use at 500°C appears to be practical.

Tribological properties are not attributes of one material alone but of one material sliding on another with, almost always, a third in between. The number of combinations is far too great to allow choice in a simple, systematic way. The selection of materials for bearings, drives, and sliding seals relies heavily on experience. This experience is captured in reference sources (for which see Appendix D). In the end it is these that must be consulted. But it does help to have a feel for the magnitude of friction coefficients and wear rates and to have an idea of how these relate to material class.

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. 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 that is independent of the apparent, nominal area of contact A_n . The coefficient friction μ is defined by

$$\mu = \frac{F_s}{F_n} \quad (4.22)$$

Approximate values for μ for dry, unlubricated, sliding of materials on a steel counterface are shown in Figure 4.15. 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

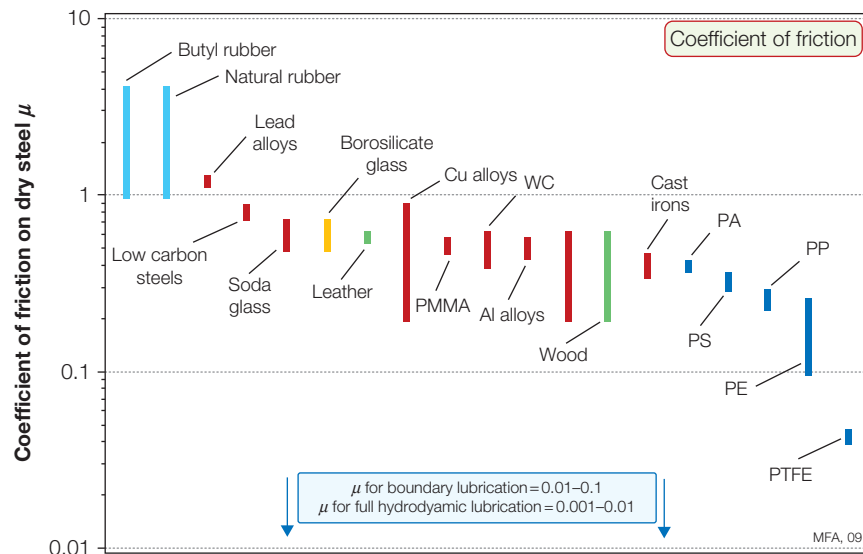


FIGURE 4.15

The friction coefficient μ of materials sliding on an unlubricated steel counterface.

because one surface has a sufficiently low modulus that it conforms to the other (rubber on rough concrete). At the other extreme are sliding combinations with exceptionally low coefficients of friction, such as PTFE or bronze bearings loaded with graphite sliding on polished steel. Here the coefficient of friction falls as low as 0.04, although this is still high compared with friction for lubricated surfaces, as noted at the bottom of the diagram.

When surfaces slide, they wear. Material is lost from both surfaces, even when one is much harder than the other. The *wear rate* W (units: m^3) is conventionally defined as

$$W = \frac{\text{Volume of material removed from contact surface}}{\text{Distance slid}} \quad (4.23)$$

A more useful quantity, for our purposes, is the specific wear rate

$$\Omega = \frac{W}{A_n} \quad (4.24)$$

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

$$k_a = \frac{W}{F_n} = \frac{\Omega}{P} \quad (4.25)$$

is roughly constant. The *wear-rate constant* k_a (units: $(\text{MPa})^{-1}$) is a measure of the propensity of a sliding couple for wear: High k_a means rapid wear at a given bearing pressure.

The bearing pressure P is the quantity specified by the design. The ability of a surface to resist a static contact pressure is measured by its hardness H , so we anticipate that the maximum bearing pressure $P_{\max}$ should scale with the hardness of the softer surface:

$$P_{\max} = CH$$

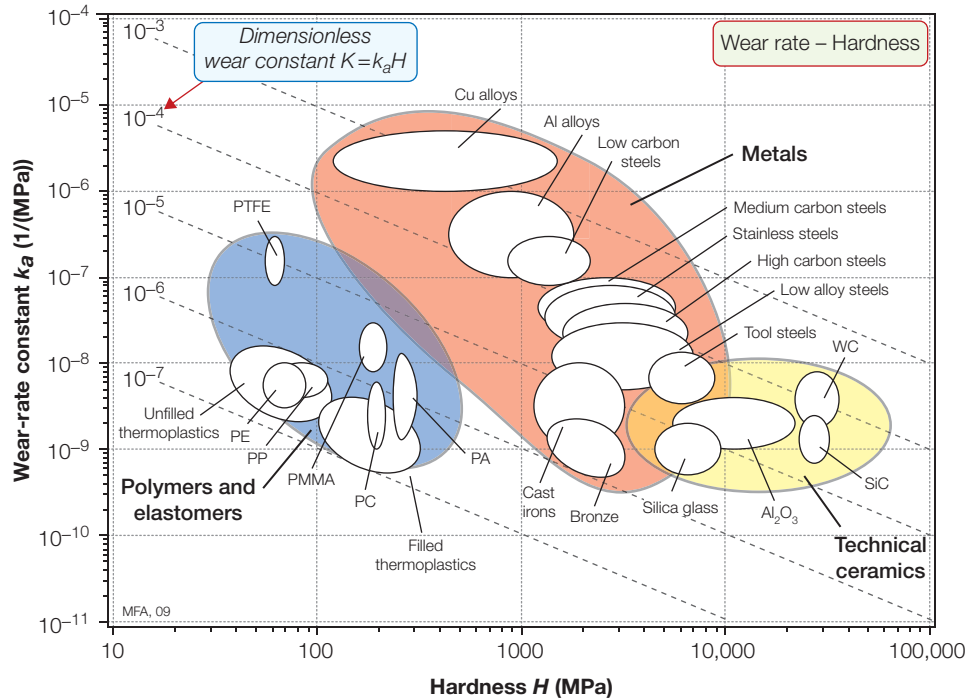
where C is a constant. Thus the wear rate of a bearing surface can be written as

$$\Omega = k_a P = C \left(\frac{P}{P_{\max}} \right) k_a H \quad (4.26)$$

Two material properties appear in this equation: the wear-rate constant k_a and the hardness, H . They are plotted in [Figure 4.16](#). The dimensionless quantity

$$K = k_a H \quad (4.27)$$

is shown as a set of diagonal contours. Note first that materials of a given class (metals, for instance) tend to lie along a downward-sloping diagonal across the figure, reflecting the fact that low wear rate is associated with high hardness. The best materials for bearings for a given bearing pressure

**FIGURE 4.16**

The normalized wear rate k_a plotted against hardness H , here expressed in MPa rather than Vickers (H in MPa = $10 H_V$). The chart gives an overview of the way in which common engineering materials behave.

P are those with the lowest value of k_a , that is, those nearest the bottom of the diagram. On the other hand, an efficient bearing, in terms of size or weight, will be loaded to a safe fraction of its maximum bearing pressure, that is, to a constant value of $P/P_{\max}$; for these, materials with the lowest values of the product $k_a H$ are best.

Cost bar charts

Properties like modulus, strength, and conductivity do not change with time. Cost is bothersome because it does. Supply, scarcity, speculation, and

Materials for bearings

Use Figure 4.16 to find two metals and two polymers that offer good wear resistance at constant bearing pressure.

Answer

The figure suggests bronze, cast iron, polycarbonate (PC), and nylon (PA) as good choices.

inflation contribute to 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 Figures 4.17(a) and (b). Most commodity

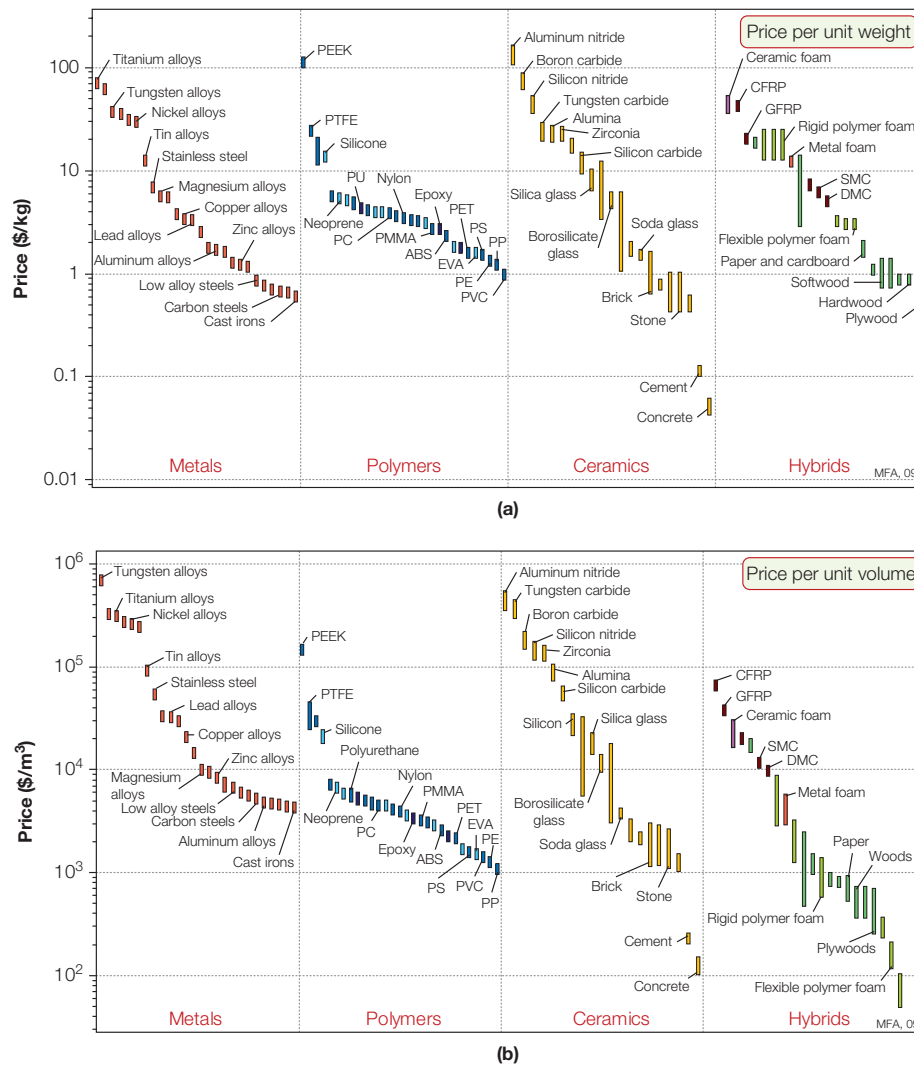


FIGURE 4.17

(a) The approximate price/kg of materials. Commodity materials cost about \$1/kg; special materials cost much more.
 (b) The approximate price/ m^3 of materials. Polymers, because they have low densities, cost less per unit volume than most other materials.

Polymer prices

Which four polymers are the least expensive?

Answer

Figure 4.17 shows that the four least expensive polymers, either by weight or by volume, are polypropylene (PP), polyethylene (PE), polyvinylchloride (PVC), and polystyrene (PS). These are the commodity polymers—the ones used in the greatest quantities.

Relative price

Are polypropylene and polyethylene more or less expensive than steel per unit weight? What about per unit volume?

Answer

Figure 4.17 reveals that the two polymers are more expensive than steel per unit weight, but because they have much lower densities, they are cheaper per unit volume. If we want a proper comparison, what should be the basis of comparison? The answer, developed in later chapters, is *per unit function*.

materials (glass, steel, aluminum, and the common polymers) cost between 0.5 and 2.0 \$/kg. Because they have low densities, the cost/m³ of commodity polymers is less than that of metals.

The modulus–relative cost chart

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* $C_{v,R}$.

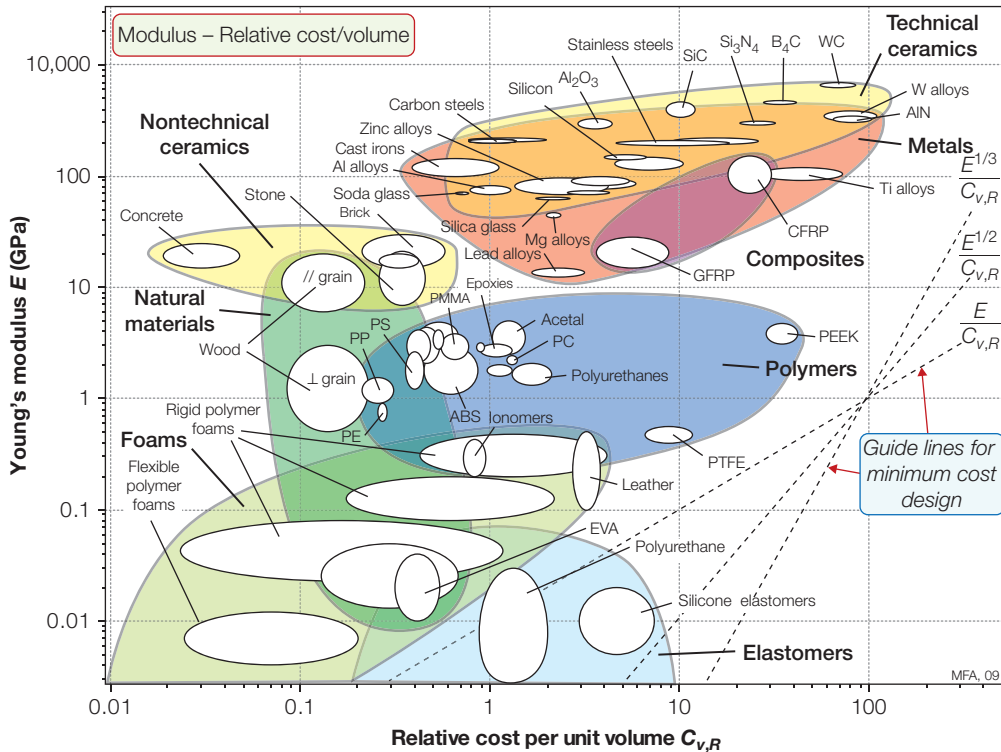
$$C_{v,R} = \frac{\text{Cost/kg} \times \text{Density of material}}{\text{Cost/kg} \times \text{Density of mild steel rod}} \quad (4.28)$$

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

Figure 4.18 shows the modulus E plotted against relative cost per unit volume $C_{v,R}\rho$ where ρ is the density. Cheap, stiff materials lie toward the top left. Guide lines for selecting materials that are stiff and cheap are plotted in the figure.

The strength–relative cost chart

Cheap strong materials are selected using Figure 4.19. It shows failure strength, defined as before, plotted against relative cost per unit volume. The qualifications for the definition of strength, given earlier, apply here also.

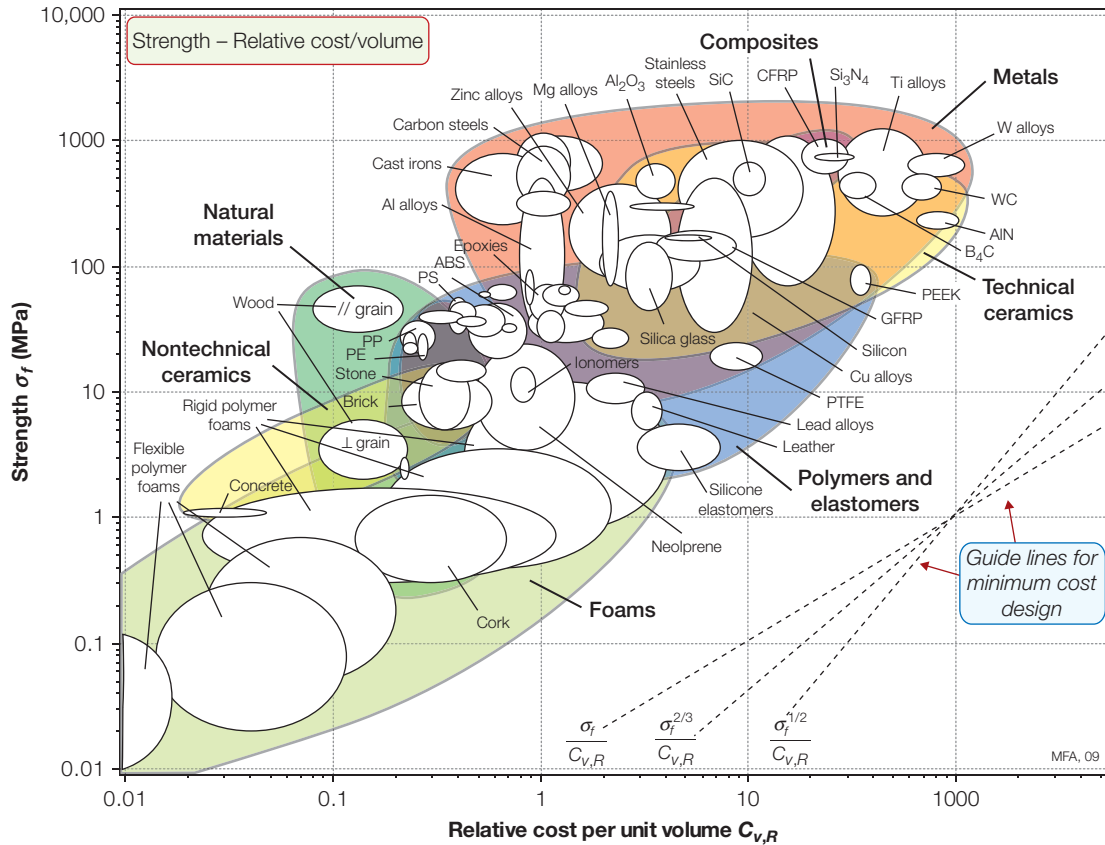
**FIGURE 4.18**

Young's modulus E plotted against relative cost per unit volume $C_{v,R}$. The design guide lines help selection to maximize stiffness per unit cost.

It must be emphasized that the data plotted here and in Figure 4.18 are less reliable than those in other charts and are 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." An example is given in Section 6.5.

4.4 SUMMARY AND CONCLUSIONS

The engineering properties of materials are usefully displayed as material selection charts. Eighteen of them are introduced in this chapter; more appear in later ones. The charts summarize material properties in a compact, easily accessible way, showing the range spanned by each material family and class. By choosing the axes in a sensible way, more information can be displayed. A chart of modulus E against density ρ reveals the longitudinal wave velocity $(E/\rho)^{1/2}$. A chart of fracture toughness K_{Ic} against modulus E shows the

**FIGURE 4.19**

Strength σ_f plotted against relative cost per unit volume $C_{v,R}$. The design guide lines help selection to maximize strength per unit cost.

toughness G_{1c} . A chart of thermal conductivity λ against diffusivity, a , also gives the volume-specific heat ρC_v . A chart of strength, σ_f , against modulus, E , shows the energy-storing capacity, σ_f^2/E , and there are many more.

The most striking feature of the charts is the way in which members of a material class cluster together. Despite the wide range of modulus and density of metals (as an example), the clusters occupy a field that is distinct from that of polymers or that of ceramic, or that of composites. The same is true of strength, toughness, thermal conductivity, and the rest: The fields frequently overlap, but they always have a characteristic place within the whole picture.

The position of the fields and their relationship can be understood in simple physical terms. The nature of the bonding, the packing density, the lattice resistance, and the vibrational modes of the structure are themselves a function of

bonding and packing. It may seem odd that so little mention has been made of microstructure in determining properties. But the charts clearly show that the first-order difference between the properties of materials has its origins in the mass of the atoms, the nature of the inter-atomic forces, and the geometry of packing. Alloying, heat treatment, and mechanical working, to which we return in Chapter 13, all influence microstructure and, through this, properties, giving the elongated bubbles shown on many of the charts; but the magnitude of their effect is less, by factors of 10, than that of bonding and structure.

All the charts have one thing in common: Parts of them are populated with materials and parts are not. Some parts are inaccessible for fundamental reasons that relate to the size of their atoms and the nature of the forces that bind their atoms together. But other parts are empty even though, in principle, they are accessible. If they were accessed, the new materials that lie there could allow novel design possibilities. Ways of doing this are explored further in Chapters 11 and 12.

The charts have numerous applications. One is the checking and validation of data (Appendix A); here use is made of both the range covered by the envelope of material properties and the numerous relations between them (like $E\Omega = 100kT_m$), described in Section 4.3. Another concerns the development of, and identification of uses for, new materials; materials that fill gaps in one or more of the charts generally offer some improved design potential. But most important of all, the charts form the basis for a procedure for materials selection. That is developed in the following chapters.

4.5 FURTHER READING

The best general book on the physical origins of the mechanical properties of materials remains that by Cottrell (1964).

Ashby, M.F., Shercliff, H.R., & Cebon, D. (2009). *Materials: Engineering, science, processing and design* (2nd ed.). Butterworth-Heinemann, ISBN 978-1-85617-895-2.

An elementary text that introduces materials through material property charts and develops the selection methods through case studies.

Budinski, K.G., & Budinski, M.K. (2010). *Engineering materials, properties and selection* (9th ed.). Prentice Hall, ISBN 978-0-13-712842-6.

A well-established materials text that deals well with both material properties and processes.

Cottrell, A.H. (1964). *Mechanical properties of matter*. Wiley, Library of Congress Number 65-14262.

An inspirational book, clear, full of insights and simple derivations of the basic equations describing the mechanical behavior of solids, liquids, and gases.

Dieter, G.E. (1999). *Engineering design, a materials and processing approach* (3rd ed.). McGraw-Hill, ISBN 9-780-073-66136-0.

A well-balanced and respected text focusing on the place of materials and processing in technical design.

Farag, M.M. (2008). *Materials and process selection for engineering design* (2nd ed.). CRC Press, Taylor and Francis, ISBN 9-781-420-06308-0.

A materials science approach to the selection of materials.

Shackelford, J.F. (2009). *Introduction to materials science for engineers* (7th ed.). Prentice Hall, ISBN 978-0-13-601260-3.

A well-established materials text with a design slant.

Tabor, D. (1978). *Properties of matter*. Penguin Books.

This text, like that of Cottrell, is notable for its clarity and physical insight.