الجامعة التكنولوجية

قسم هندسة المواد

Department of Materials Engineering

Selection of Engineering Mat.s
Lec-5 Stiffness & Fracture Toughness Charts

By

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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

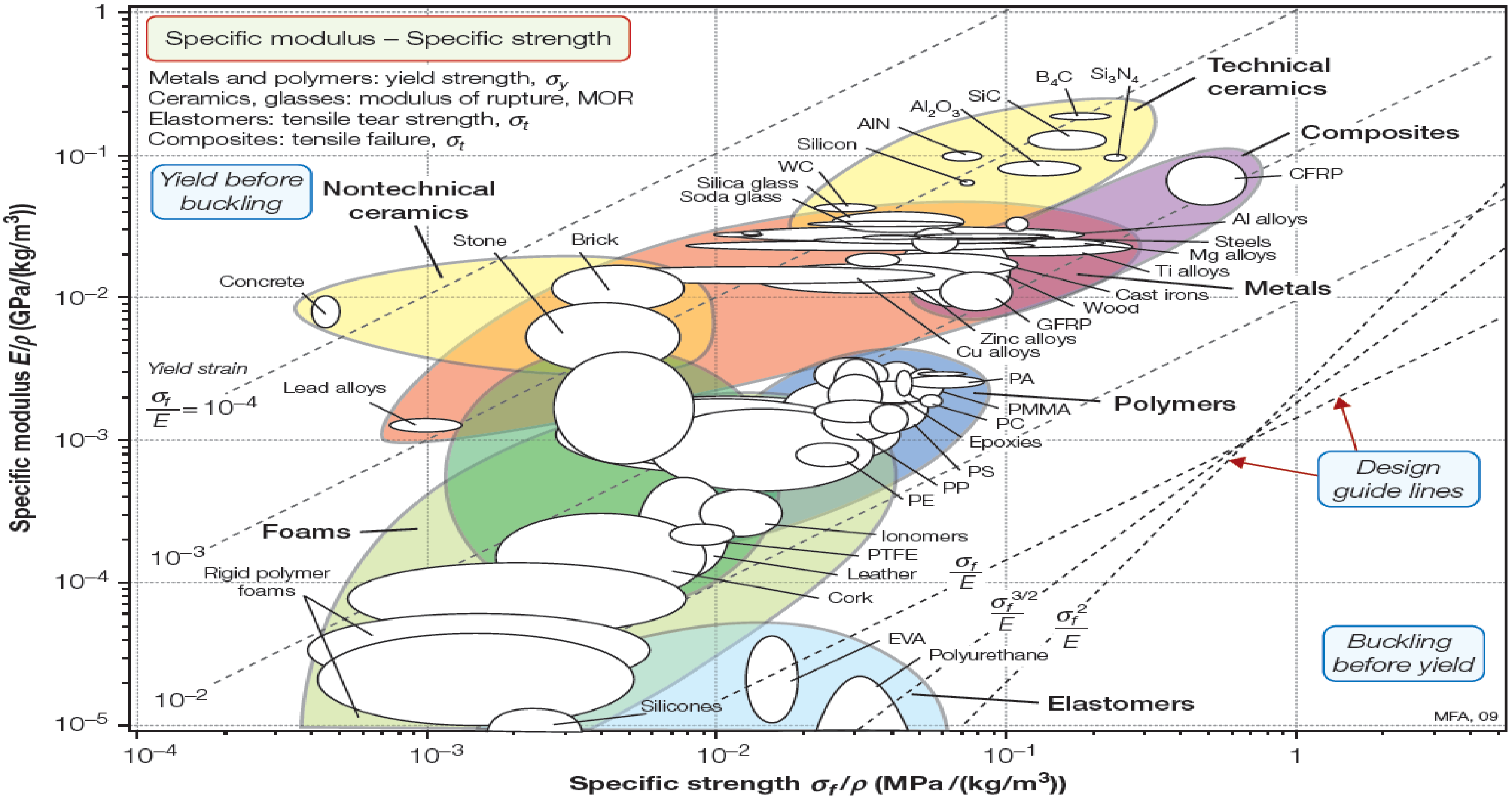


FIGURE 4.6

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.

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.

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.

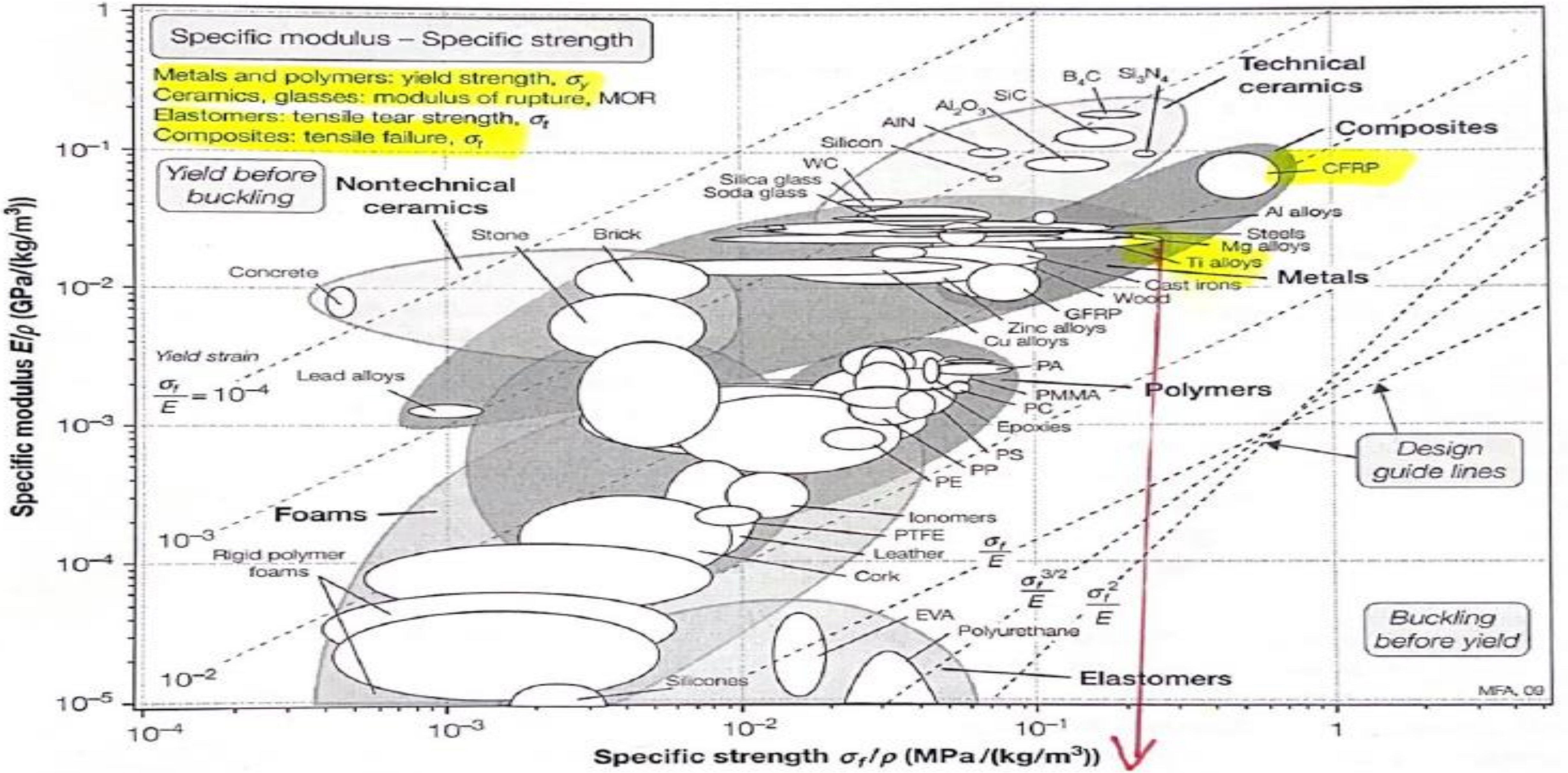


FIGURE 4.6

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.

The fracture toughness–modulus chart

Increasing the strength of a material is useful only as long as the material remains plastic and does not become brittle; if it does, it is vulnerable to failure by fast fracture initiated from any tiny crack or defect it may contain. The resistance to the propagation of a crack is measured by the *fracture toughness*, K_{1c}, the units of which are MPa.m$^{1/2}$. It is plotted against modulus E in Figure 4.7. Values range from less than 0.01 to over 100 MPa.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_{1c} are approximate, derived from critical J-integral (J_c) and critical crack-opening displacement (δ_c) measurements, by writing $K_{1c} = (EJ_c)^{1/2}$, 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_{1c} above 18 MPa.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

$$G \geq 2\gamma \tag{4.5}$$

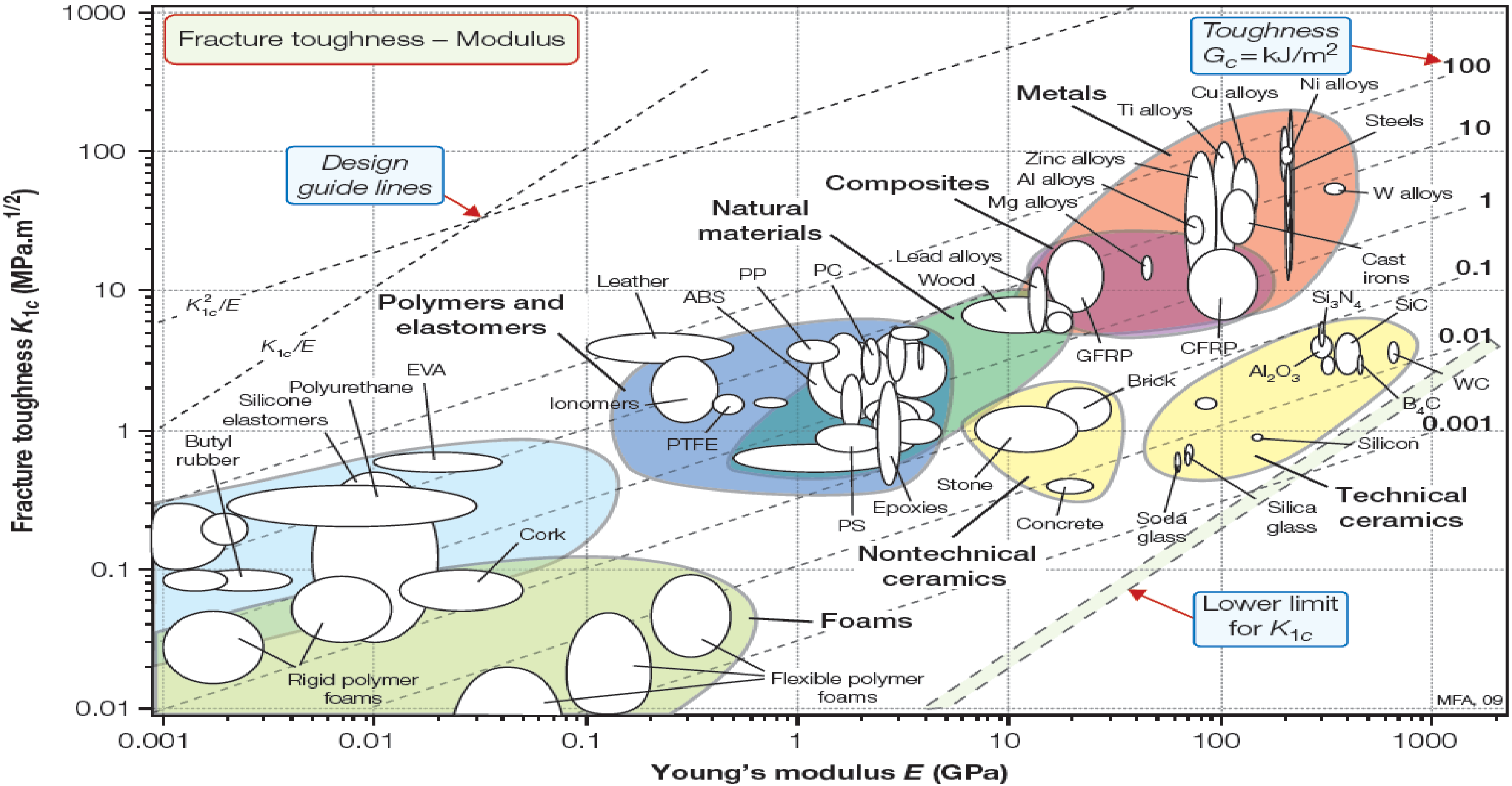


FIGURE 4.7

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

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

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

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

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,

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

This criterion is plotted on the chart as a shaded, diagonal band near the lower right corner. It defines a *lower limit* for K_{1c}. 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 $(K_1)_{scc}$ meaning "the critical value of K_1 for stress-corrosion cracking" or $(\Delta K_1)_{threshold}$ meaning "the minimum range of K_1 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 ($G_c \approx K_{1c}^2/E$). The true surface energies, γ, of solids lie in the range 10^{-4} to 10^{-3} kJ/m^2. The diagram shows that the values of the toughness start at 10^{-3} kJ/m^2 and range through almost five decades to over 100 kJ/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.

Comparing materials by toughness

The fracture toughness K_{1c} of polypropylene (PP) is about 4 MPa.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.

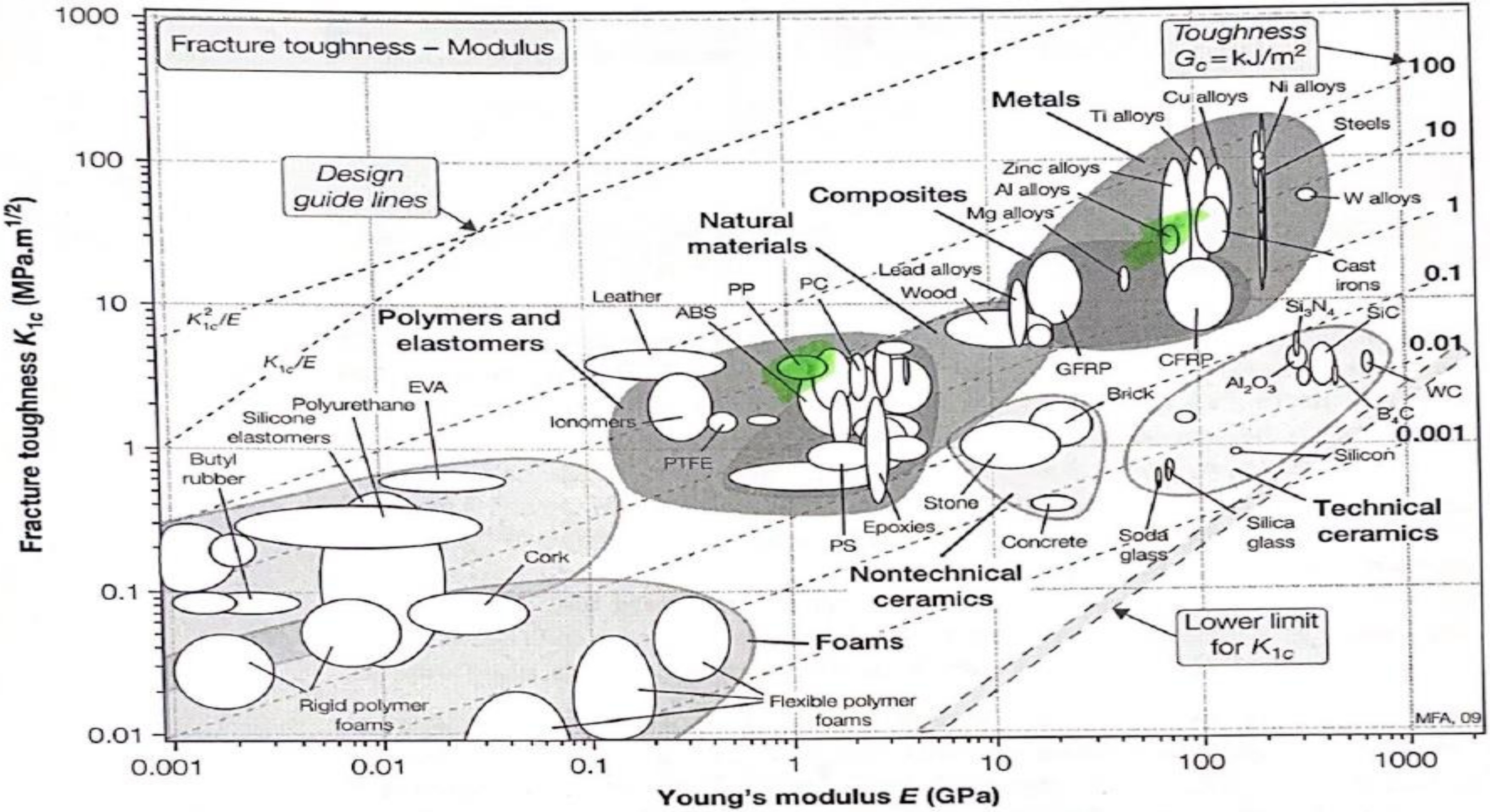


FIGURE 4.7

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

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

$$d_y = \frac{K_{1c}^2}{\pi \sigma_f^2} \tag{4.9}$$

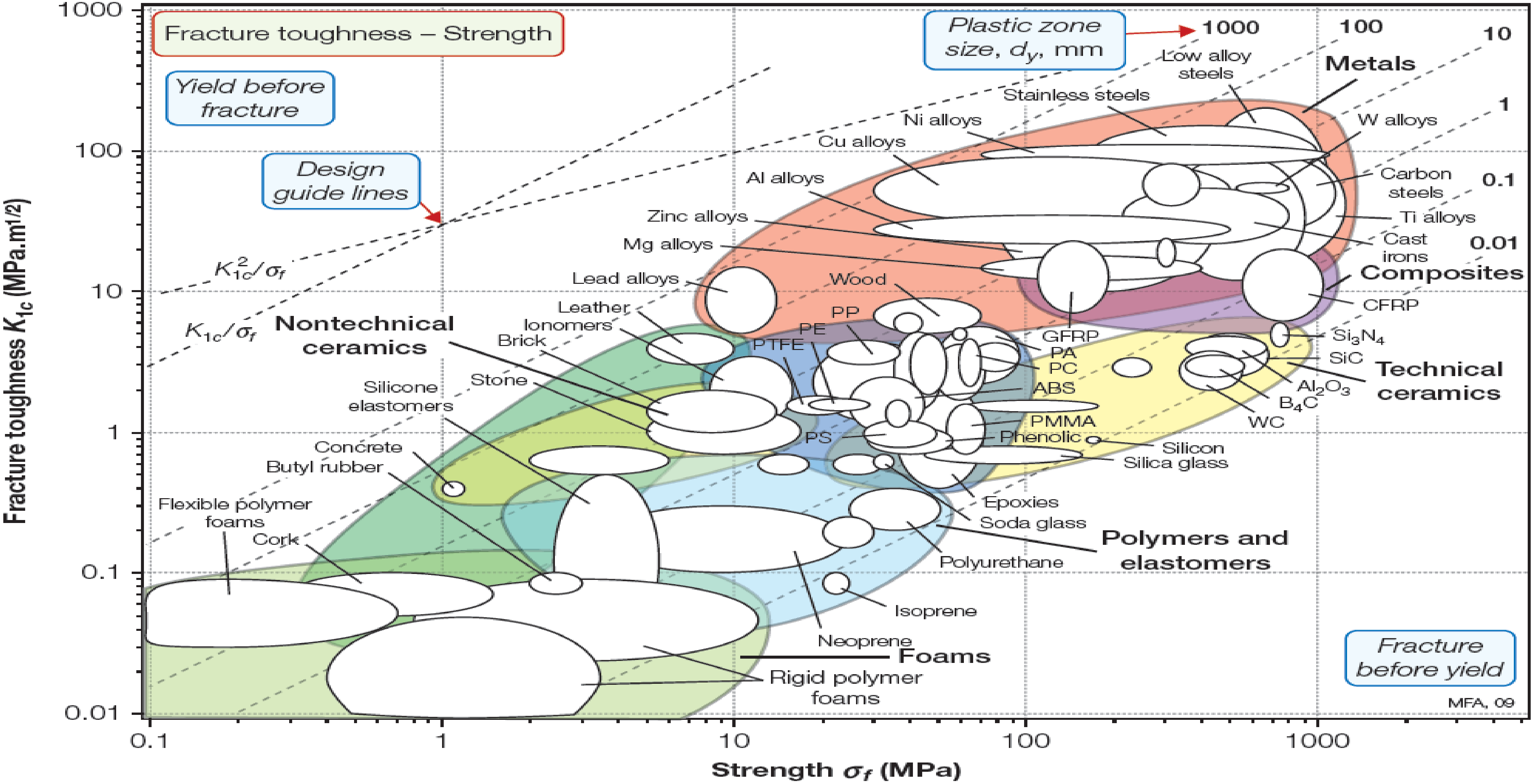


FIGURE 4.8

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*.

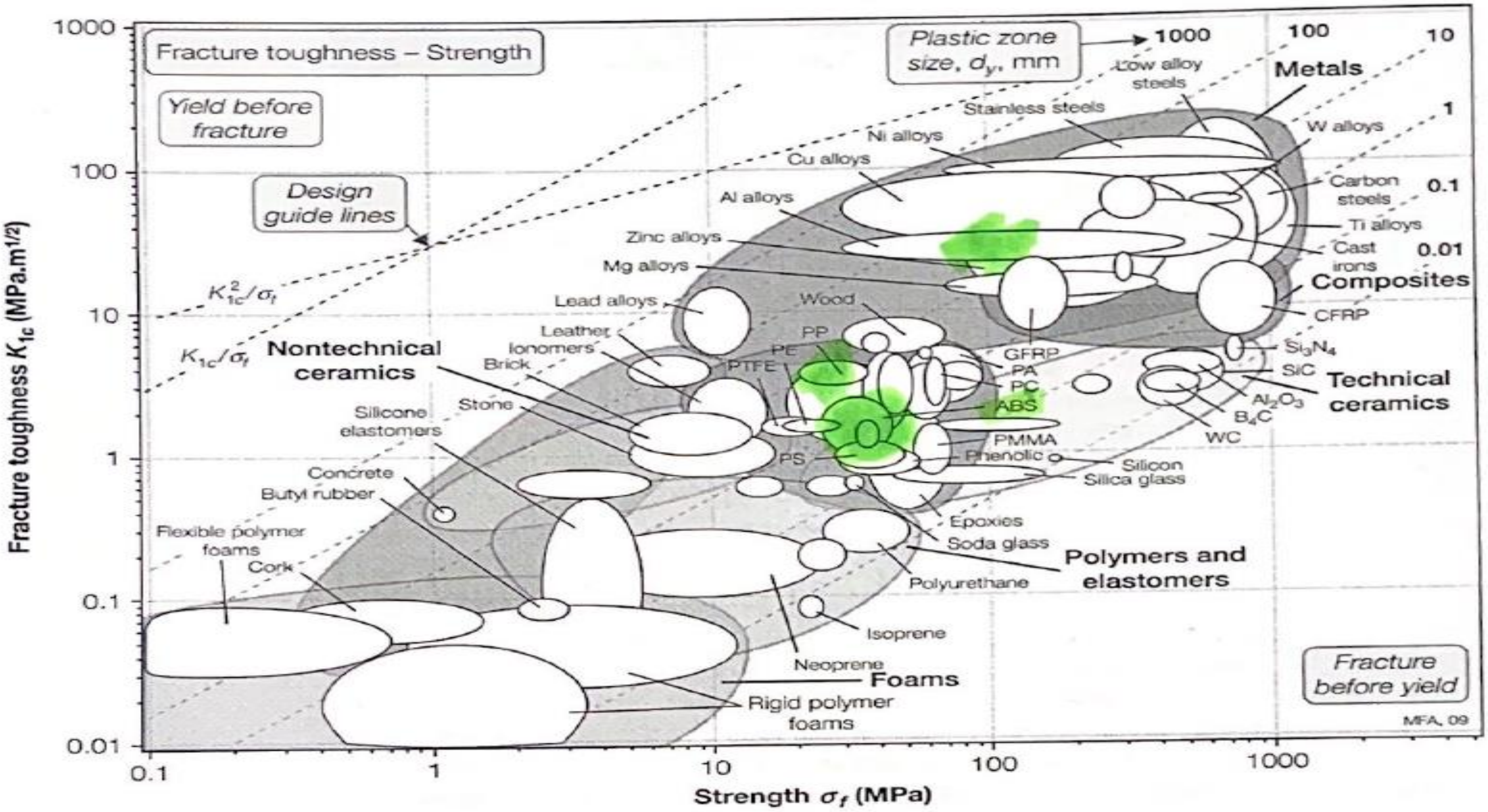
The diagram has application in selecting materials for the safe design of load-bearing structures. Examples are given in Sections 6.10 and 6.11.

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.



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