الجامعة التكنولوجية
قسم هندسة المواد
Department of Materials Engineering

Selection of Engineering Materials
Lec-4
Stength Charts

By

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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

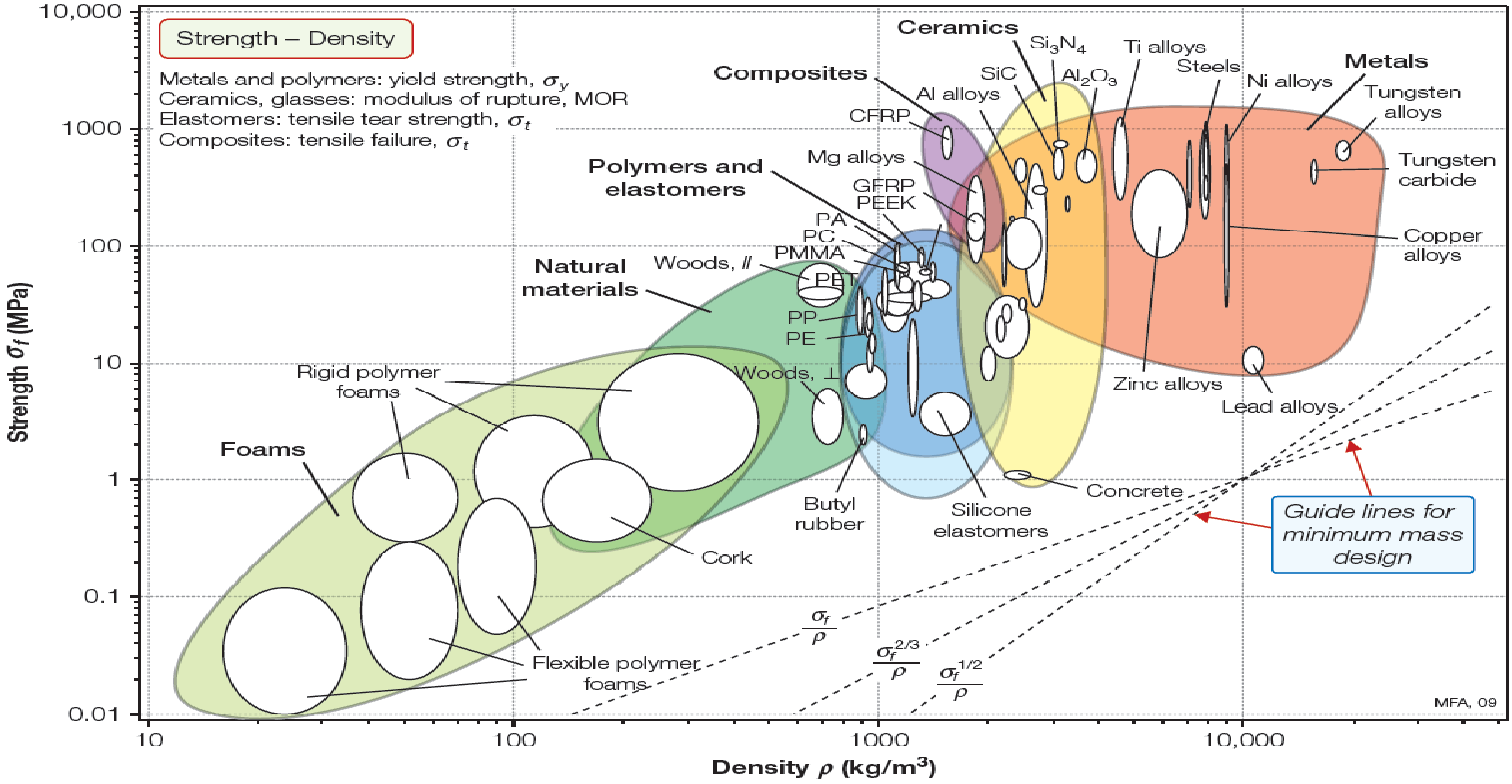


FIGURE 4.4

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 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.

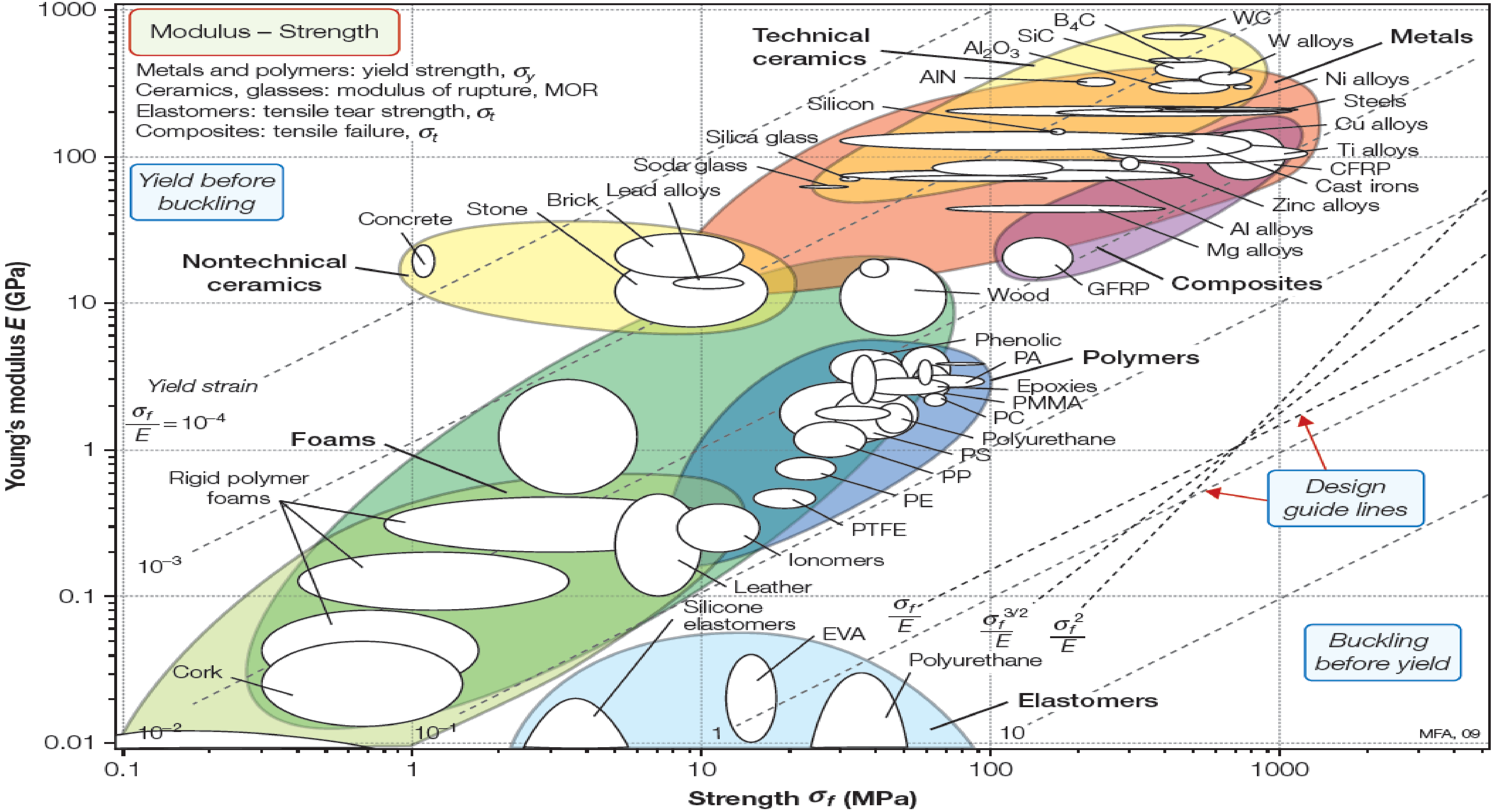


FIGURE 4.5

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.

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

$$F^* \approx \frac{Sr_o}{10} \tag{4.3}$$

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

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

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.

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.

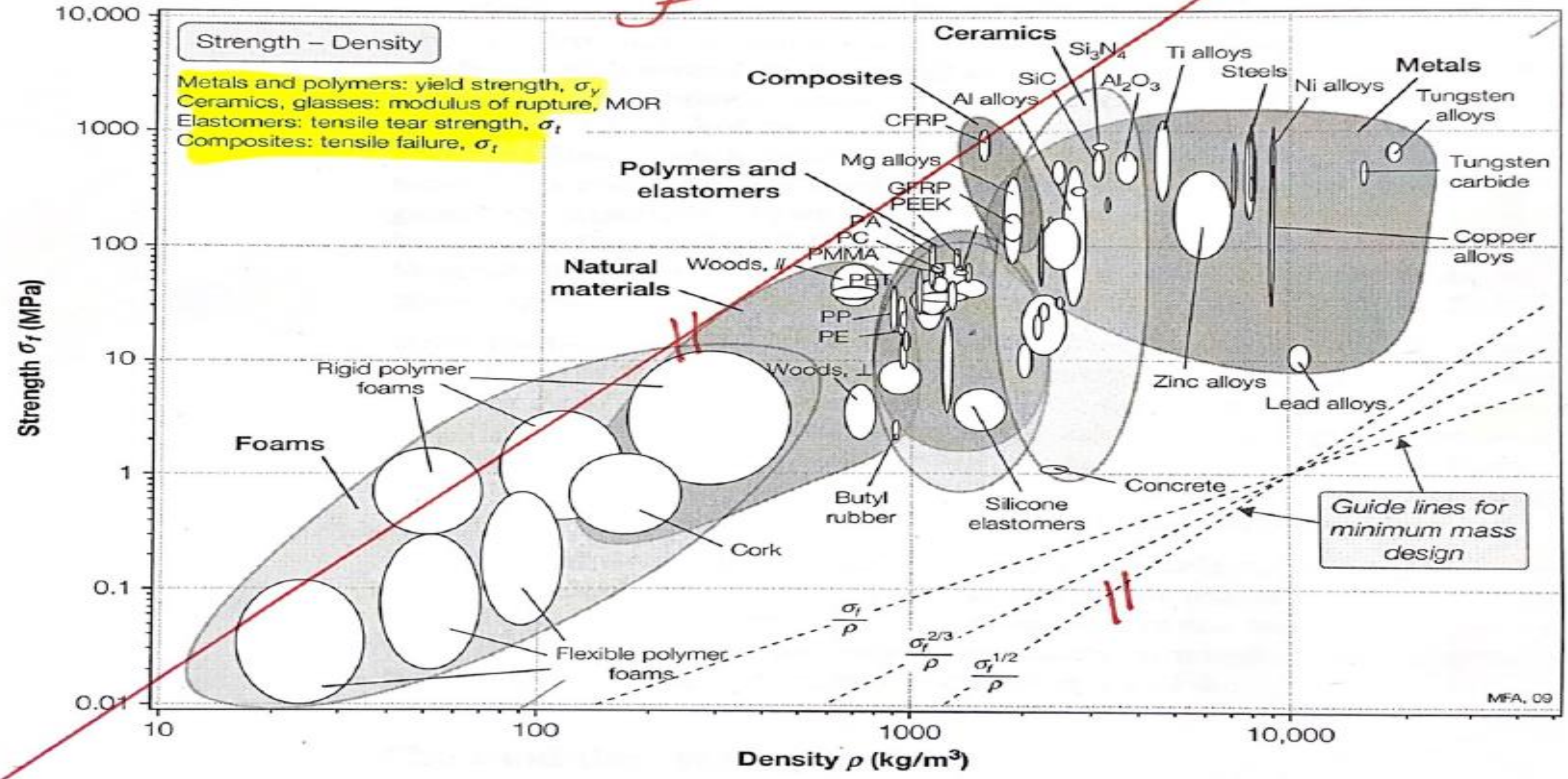
Strong solids

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.

Performance $\simeq \frac{\sigma_f^{1/2}}{\rho}$ slope = 1



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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.