الجامعة التكنولوجية
قسم هندسة المواد
Department of Materials Engineering

Selection of Engineering Mat.s
Lec-7
Friction & Wear Charts

By

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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

$$\alpha = \frac{\gamma_G \rho C_p}{3E} \tag{4.18}$$

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.

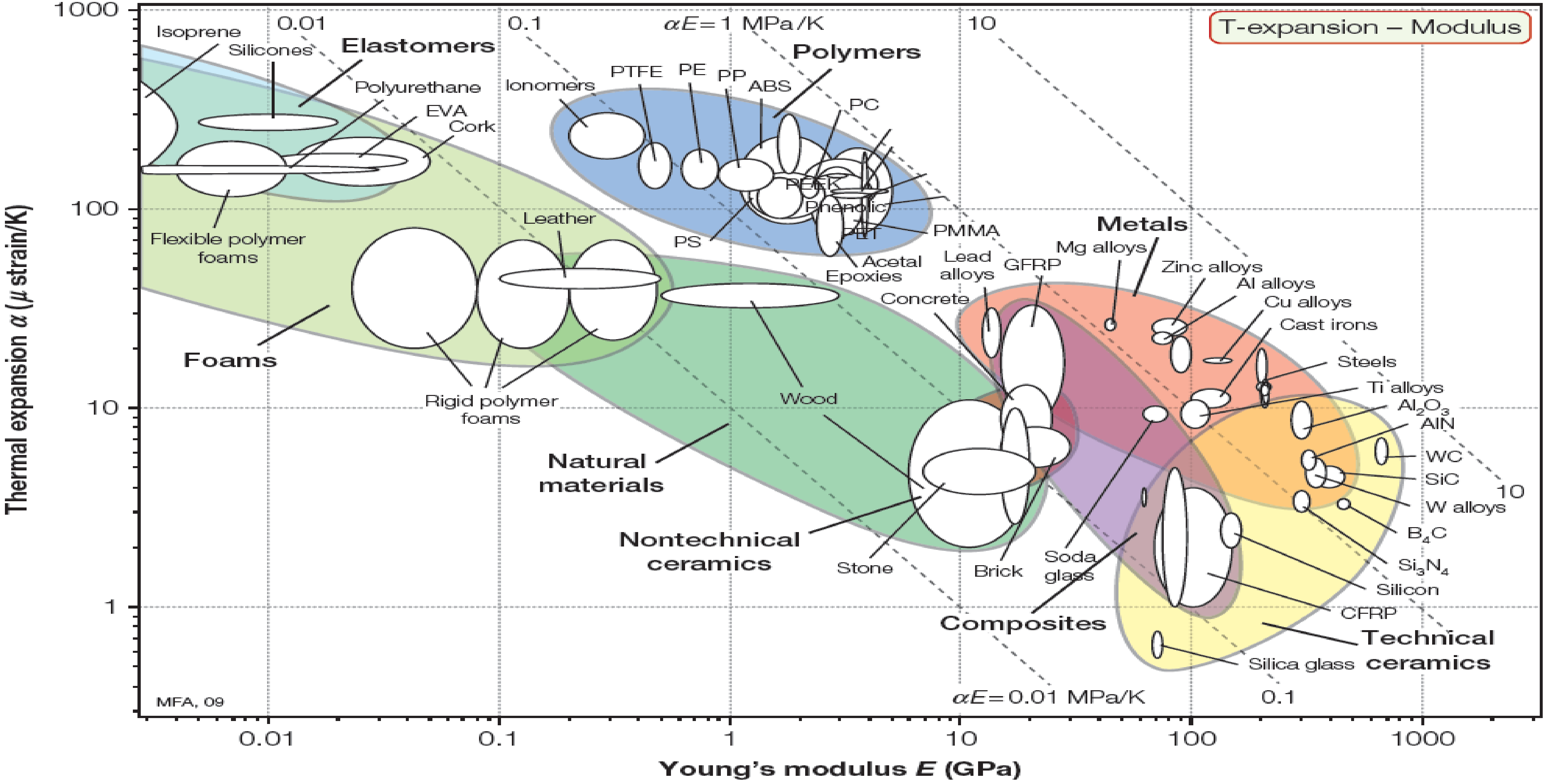


FIGURE 4.13

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:

$$E \approx \frac{100\, k\, T_m}{\Omega} \tag{4.19}$$

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

$$\alpha = \frac{\gamma_G}{100\, T_m} \tag{4.20}$$

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

$$C\,\Delta\sigma = \alpha E \tag{4.21}$$

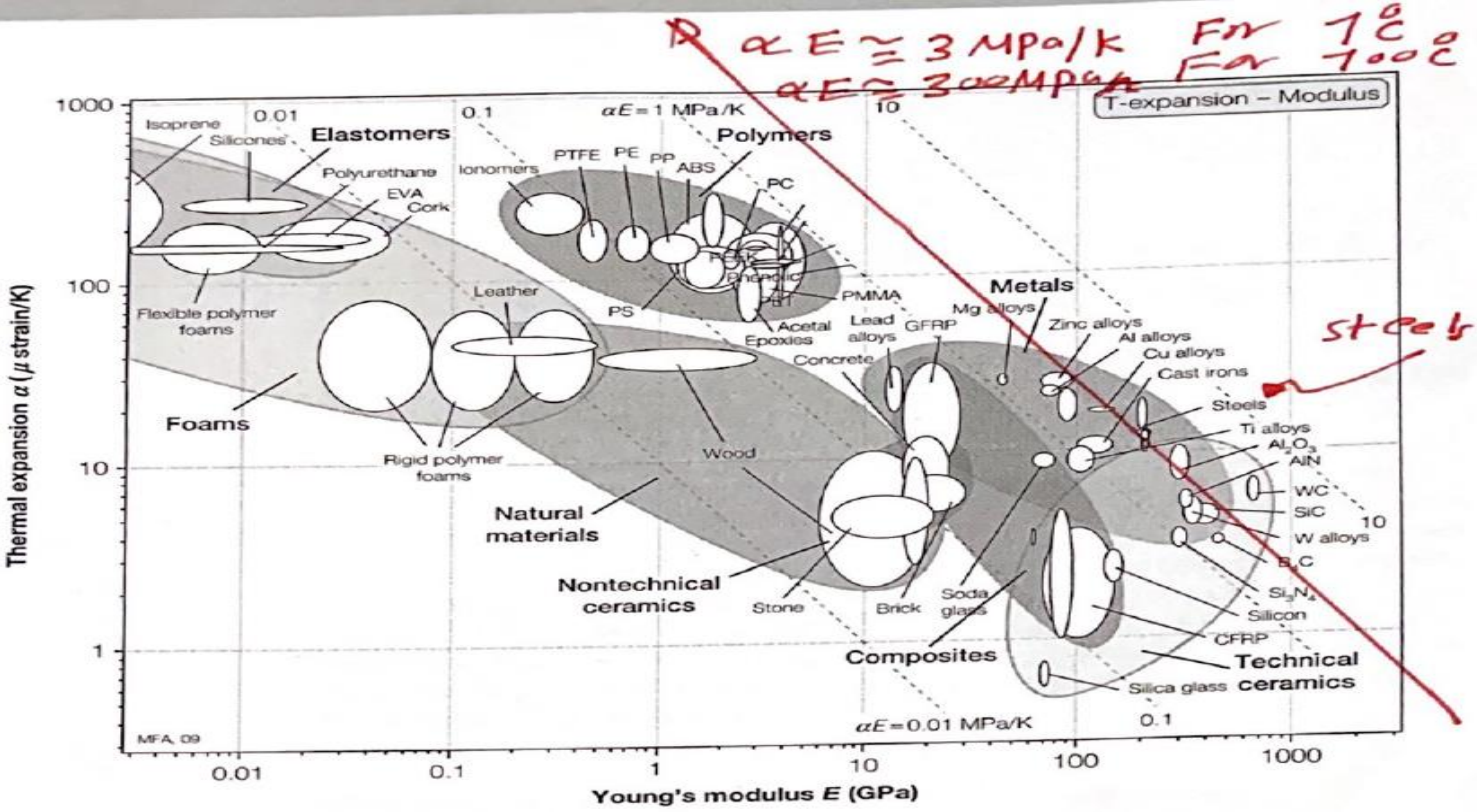
where $C = 1$ for axial constraint, $(1-\nu)$ for biaxial constraint or normal quenching, and $(1-2\nu)$ for triaxial constraint, where ν is Poisson's ratio. These stresses are large: typically 1 MPa/K. They can cause a material to yield, crack, spall, or buckle when it is suddenly heated or cooled.

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



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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.

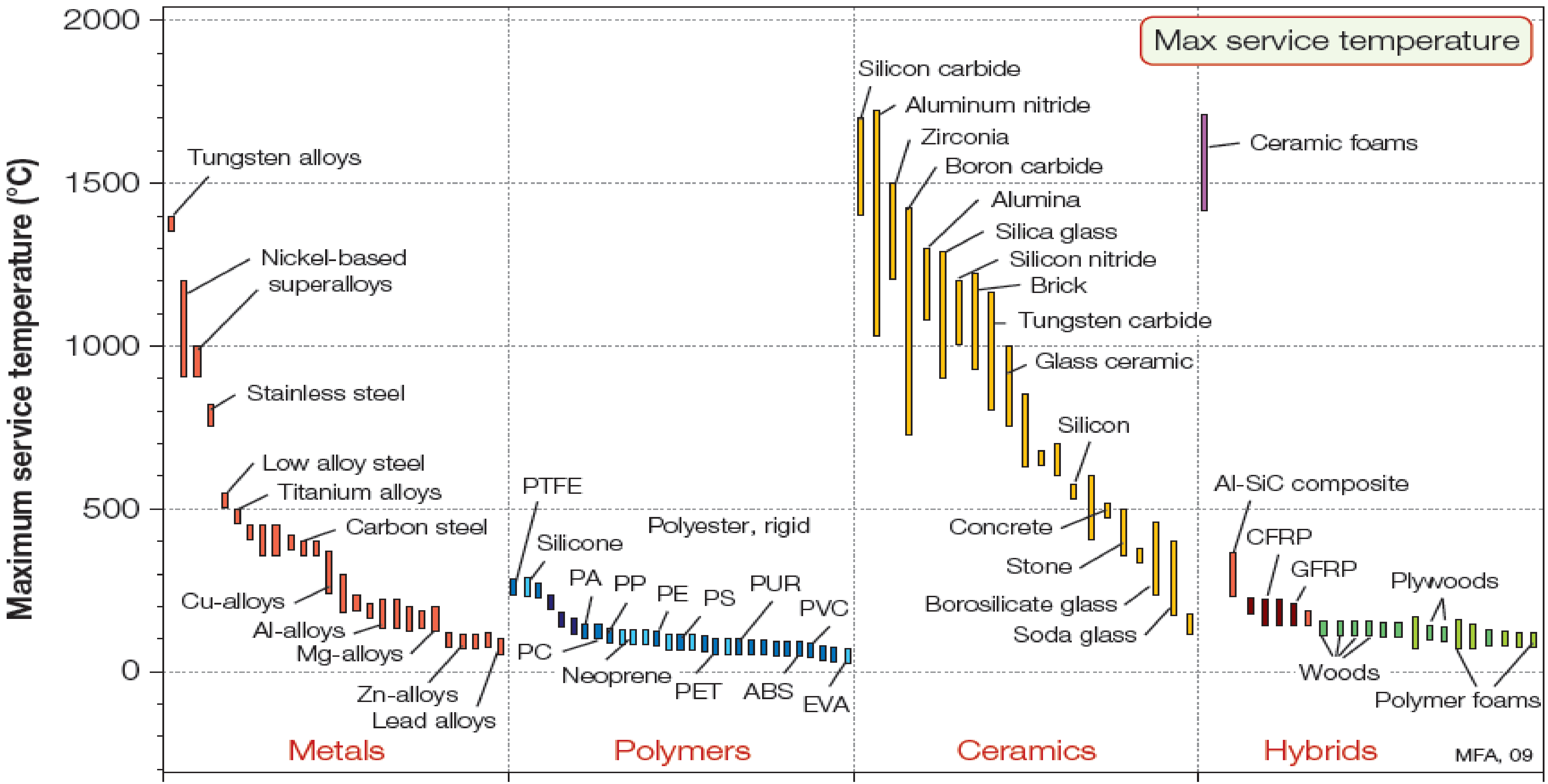


FIGURE 4.14

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

$$\mu = \frac{F_s}{F_n} \tag{4.22}$$

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

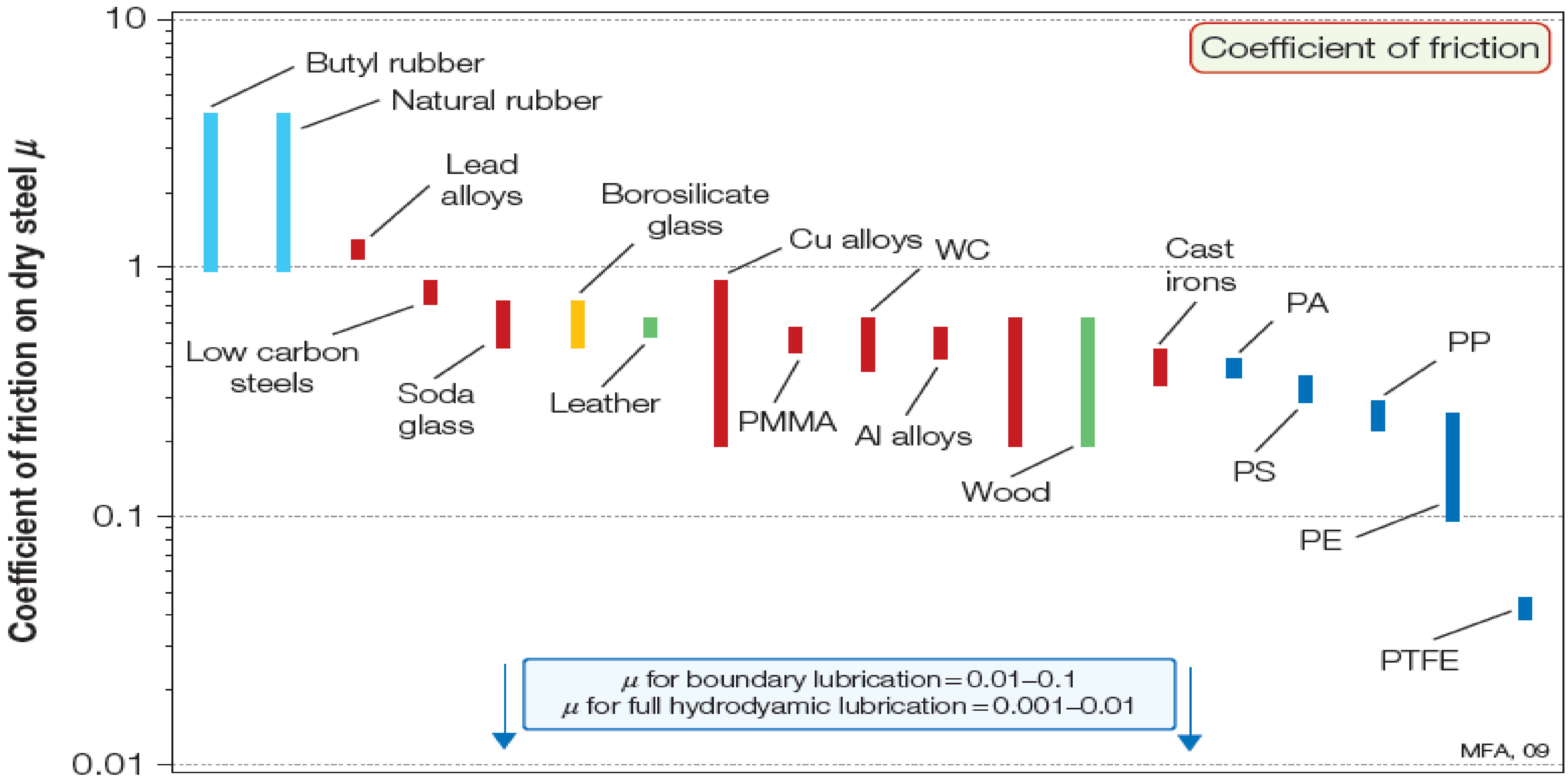


FIGURE 4.15

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^2) is conventionally defined as

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

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

$$\Omega = \frac{W}{A_n} \tag{4.24}$$

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

$$k_a = \frac{W}{F_n} = \frac{\Omega}{P} \tag{4.25}$$

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:

$$P_{\max} = C H$$

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

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

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

$$K = k_a H \tag{4.27}$$

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 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.

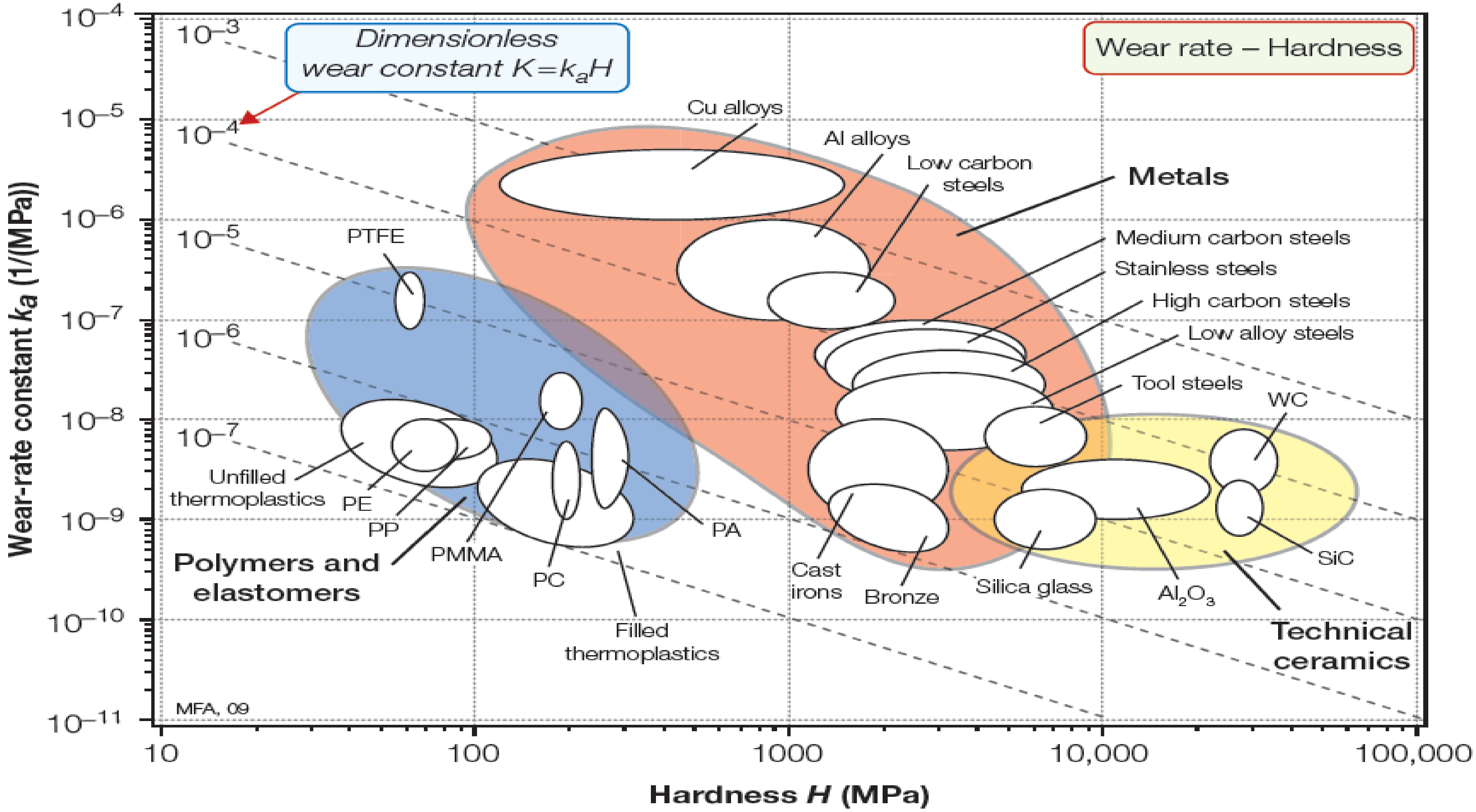


FIGURE 4.16

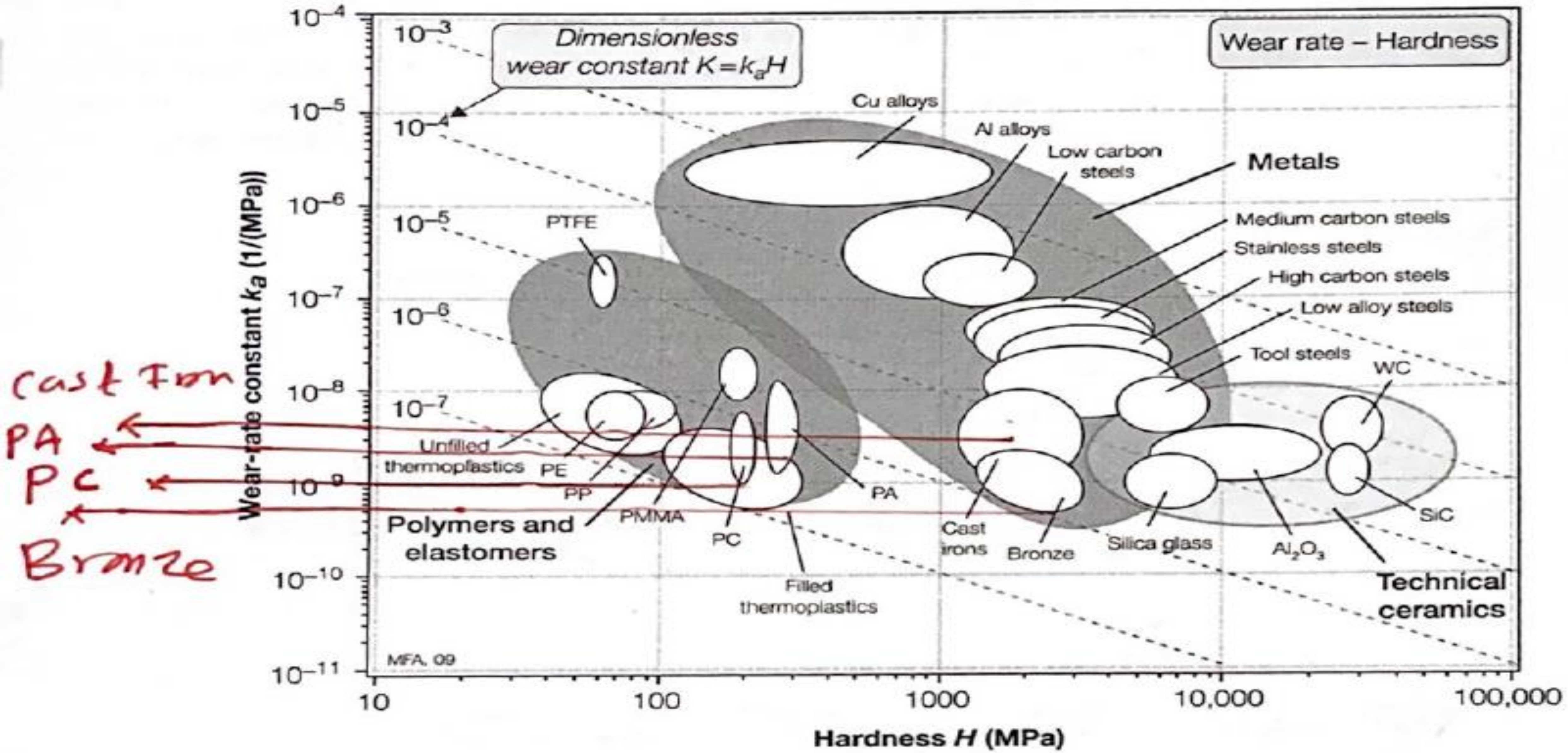
The normalized wear rate k_A plotted against hardness H, here expressed in MPa rather than Vickers (H in MPa = 10 H_v). The chart gives an overview of the way in which common engineering materials behave.

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.



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