Selection of Engineering Materials

IM 515E

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Case Study: Materials for Oars

- Boats, before steam power, could be propelled by poling, by sail and by oar.
- Oars gave more control than the other two, the military potential of which was well understood by the Romans, the Vikings and the Venetians.
- The credit for inventing the rowed boat go to the Egyptians: boats with oars appear in carved relief on monuments built in Egypt between 3300 and 3000 BC.

Materials for Oars

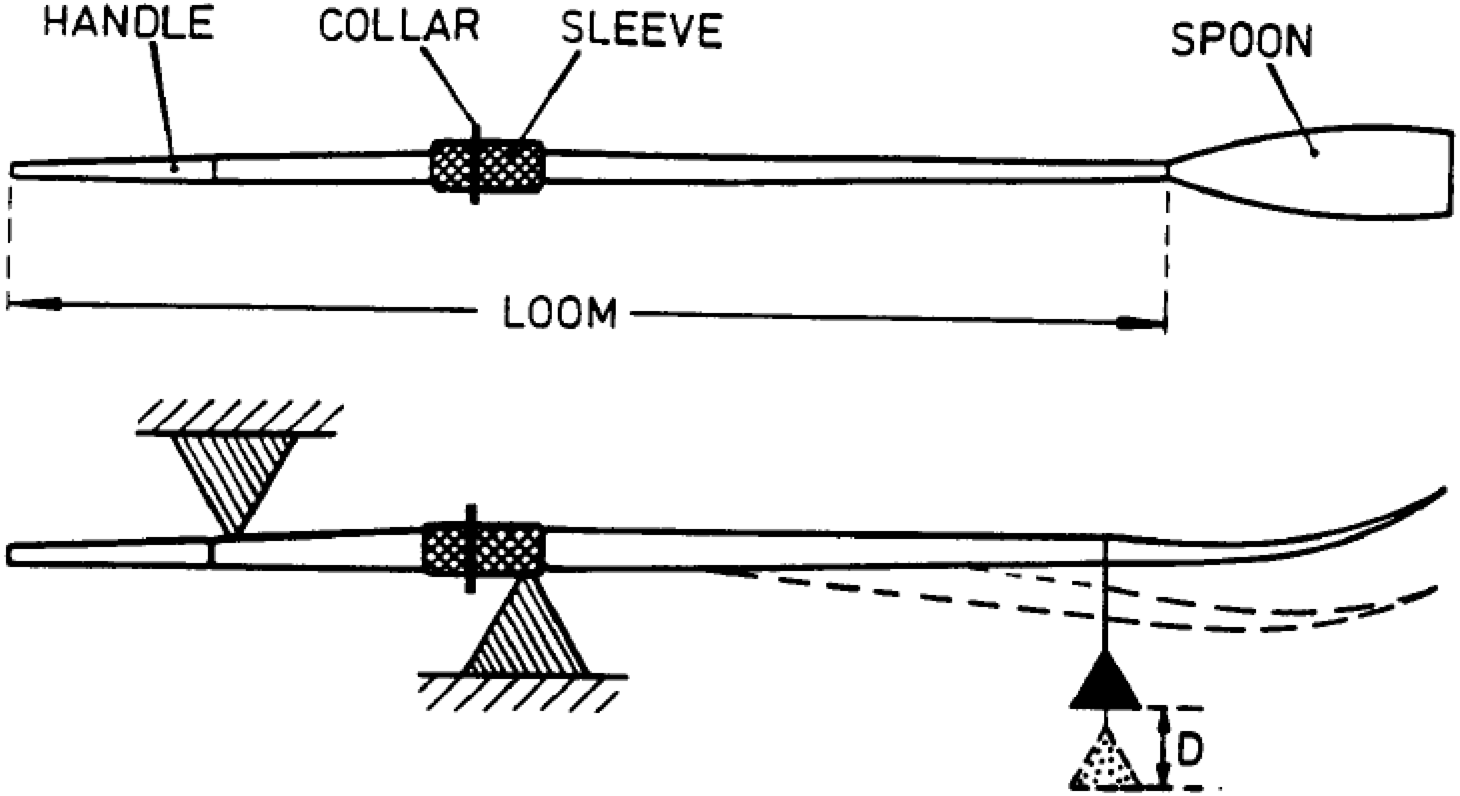


Figure1: An oar, showing the components and the method of measuring the stiffness.

Materials for Oars

- Mechanically speaking, an oar is a beam loaded in bending. It must be strong enough to carry the bending moment exerted by the oarsman without breaking.
- Therefore it must have just the right stiffness to match the rower's own characteristics and give the right "feel", and - very important – it must be as light as possible.
- Meeting the strength constraint is easy. Oars are designed on stiffness, that is, to give a specified elastic deflection under a given load.
- The upper part of figure 1 shows an oar: a blade or "spoon" is bonded to a shaft or "loom" which carries a sleeve and collar to give positive location in the rowlock.

Materials for Oars

- The lower part of the figure shows how the oar stiffness is measured: a 10 kg weight is hung on the oar 2.05 m from the collar and the deflection at this point is measured.
- A soft oar will deflect nearly 50 mm; a hard one only 30. A rower, when ordering an oar, specifies how hard it should be.
- The oar must also be light; extra weight increases the wetted area of the hull and the drag that goes with it.
- So there we have it: an oar is a beam of specified stiffness and minimum weight.

Materials for Oars

- The performance index we want was derived in earlier; it is

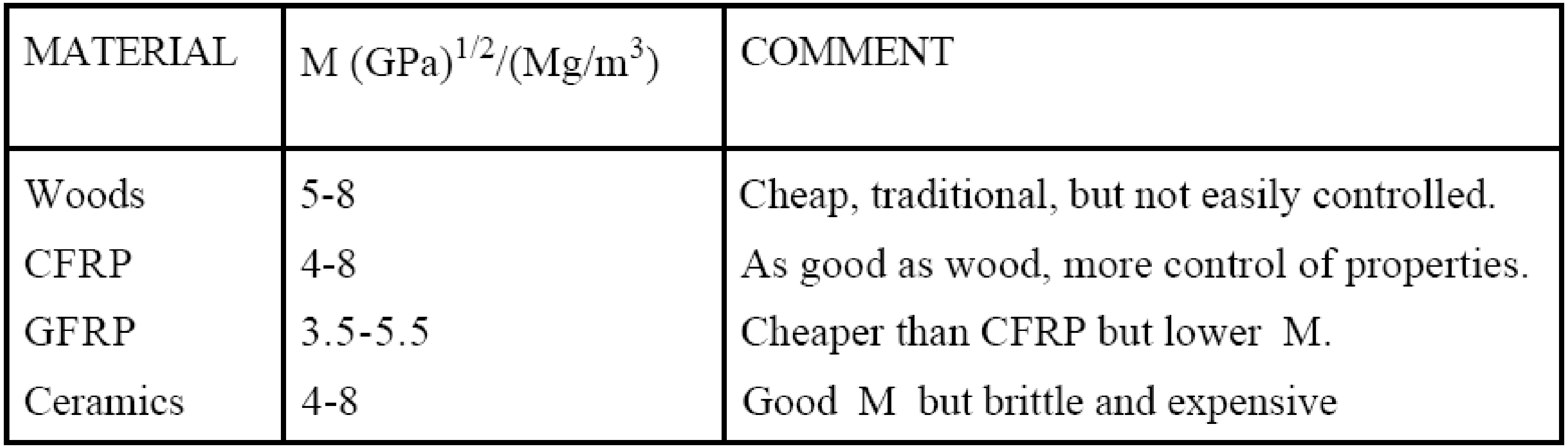
$$M_1 = \frac{E^{1/2}}{\rho}.$$

- What materials make good oars? Figure 2 shows the appropriate chart, with a selection line for the index placed on it.
- It identifies three classes of material: woods, carbon- and glass-fibre reinforced polymers and certain ceramics (Table 1).
- Ceramics are brittle; they have low values of toughness; if you dropped a ceramic oar, it would probably shatter.

Materials for Oars

- We simply note that ceramics are eliminated because they are brittle and expensive.
- The recommendation is clear. Make your oars out of wood or - better - out of CFRP.

Table 1: Materials for oars



MATERIAL	M $(GPa)^{1/2}/(Mg/m^3)$	COMMENT
Woods	5-8	Cheap, traditional, but not easily controlled.
CFRP	4-8	As good as wood, more control of properties.
GFRP	3.5-5.5	Cheaper than CFRP but lower M.
Ceramics	4-8	Good M but brittle and expensive

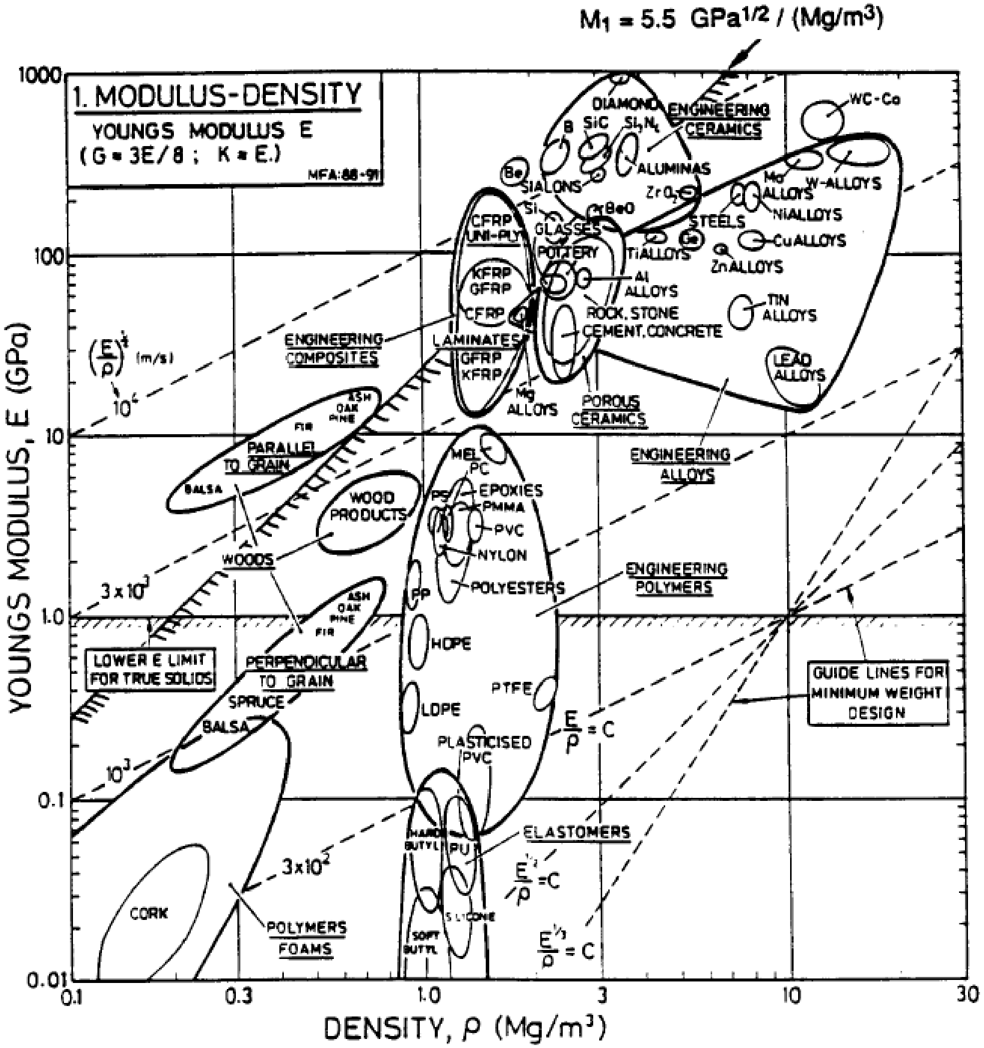


Figure 2: A modulus/density chart illustrating the selection of materials with high values of $M_1 = E^{1/2}/\rho$. Contours of constant $E^{1/2}/\rho$ appear as a family of lines of slope 2. Materials with M_1 greater than a specified value can be identified.

Materials for Oars

- Of what, in reality, are oars made? Racing oars and sculls are made either of wood or of a high performance composite: carbon-fibre reinforced epoxy, CFRP.
- Wooden oars are made today, as they were 100 years ago, by handcraftsmen who use Sitka spruce from the northern US or Canada, the further north the better because the short growing season gives a finer grain.
- A spruce oar weighs between 4 and 4.3 kg, composite blades are a little lighter than wood, for the same stiffness.

Materials for Oars

- The component parts are fabricated from a mixture of carbon and glass fibres in an epoxy matrix, assembled and glued.
- The advantage of composites lies partly in the saving of weight (typical weight: 3.9 kg) and partly in the greater control of performance: the shaft is moulded to give the stiffness specified by the purchaser.

Case Study: Materials for Precision Instruments

- The precision of a measuring device, like a sub-micrometer displacement gauge, is limited by its stiffness, and by the dimensional change caused by temperature gradients.
- Compensation for elastic deflection can be arranged; and corrections to cope with thermal expansion are possible too - provided the device is at a uniform temperature.
- Thermal gradients are the real problem: they cause a change of shape - that is, distortion - of the device for which compensation is not possible.

Materials for Precision Instruments

- Sensitivity to *vibration is also a problem: natural excitation introduces noise into the measurement.*
- So - in precision instrument design - it is permissible to allow expansion, provided distortion does not occur.
- Elastic deflection is allowed, provided natural vibration frequencies are high. What, then, are good materials for precision devices?
- Figure 3 shows, schematically, such a device: it consists of a force loop, an actuator and a sensor.

Materials for Precision Instruments

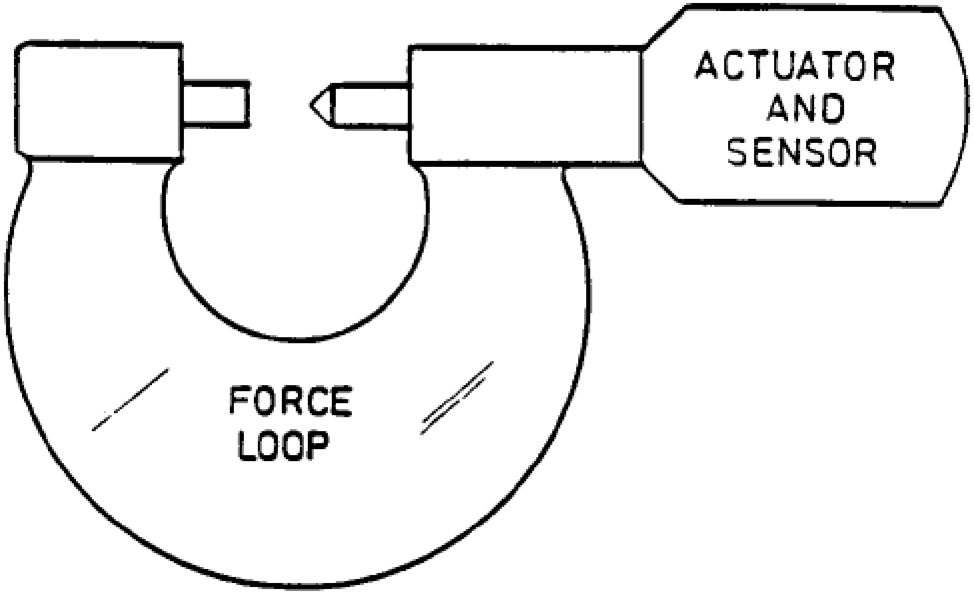


Figure 3. A precision instrument. It consists of a force loop, an actuator and a sensor

Materials for Precision Instruments

- We aim to choose a material for the force loop. It will, in general, support heat sources: electrical components which generate heat.
- The relevant performance index is found by considering the simple case of one-dimensional heat flow through a rod insulated except at its ends, one of which is at ambient and the other connected to the heat source.
- In the steady state, Fourier's law is

$$q = -\lambda \frac{dT}{dx}$$

where q is heat input per unit area, λ is the thermal conductivity and dT/dx is the resulting temperature gradient.

Materials for Precision Instruments

- The strain is related to temperature by:

$$\varepsilon = \alpha\left(T_0 - T\right)$$

where α is the thermal expansion coefficient and T_0 is ambient temperature, from which:

$$\frac{d\varepsilon}{dx} = \frac{\alpha\, dT}{dx} = \left(\frac{\alpha}{\lambda}\right)q$$

- Thus for a given geometry and heat flow, the distortion $d\varepsilon/dx$ is minimised by selecting materials with large values of the index:

$$M_3 = \frac{\lambda}{\alpha}$$

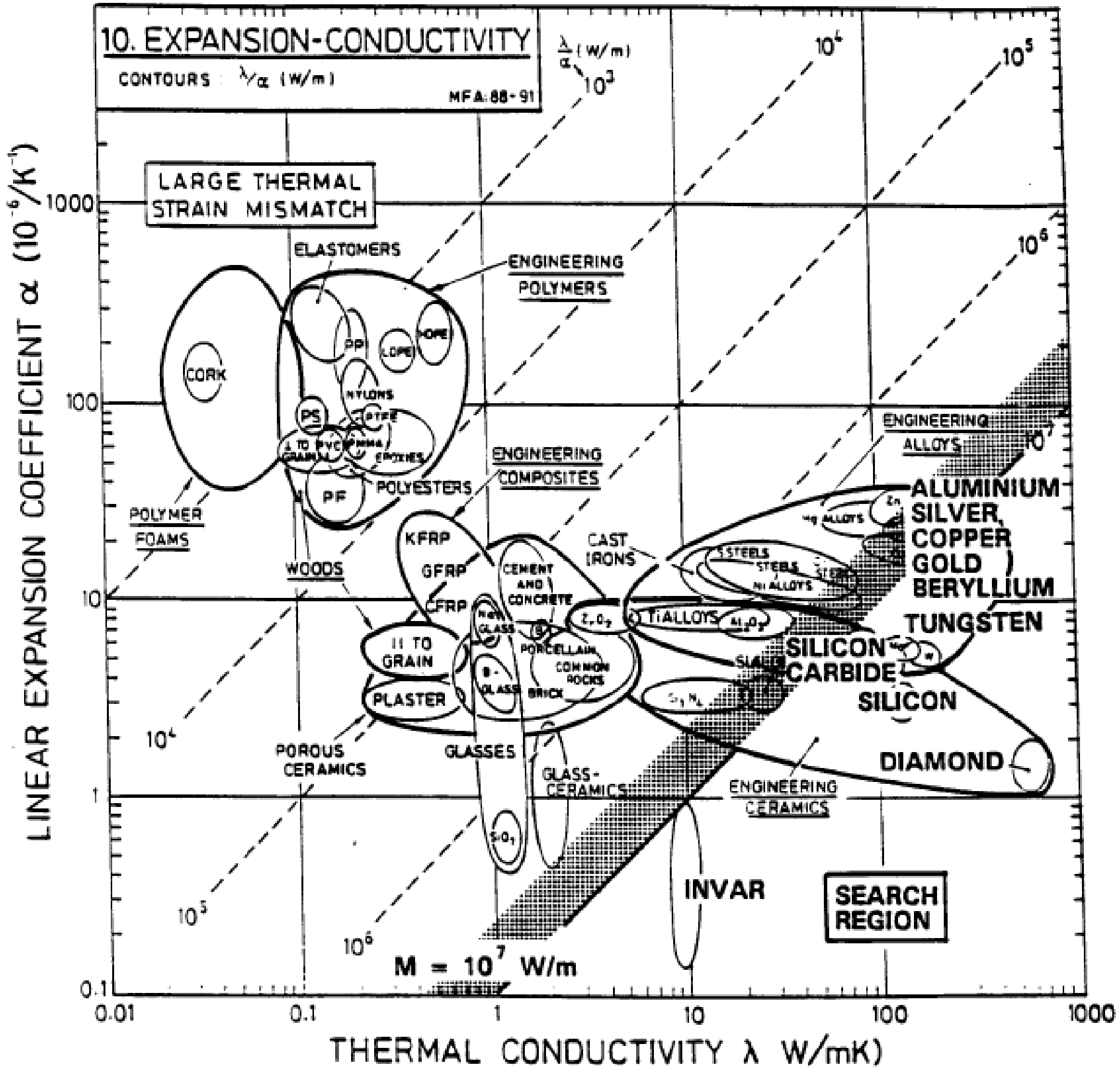


Figure 4. A Chart of thermal conductivity, λ , and expansion coefficient, α, allowing selection of materials for the force loop of precision instruments.

Materials for Precision Instruments

- The other problem is vibration. The sensitivity to external excitation is minimised by making the natural frequencies of the device as high as possible.
- The flexural vibrations have the lowest frequencies, they are proportional, once again, to:

$$M_1 = \frac{E^{1/2}}{\rho}$$

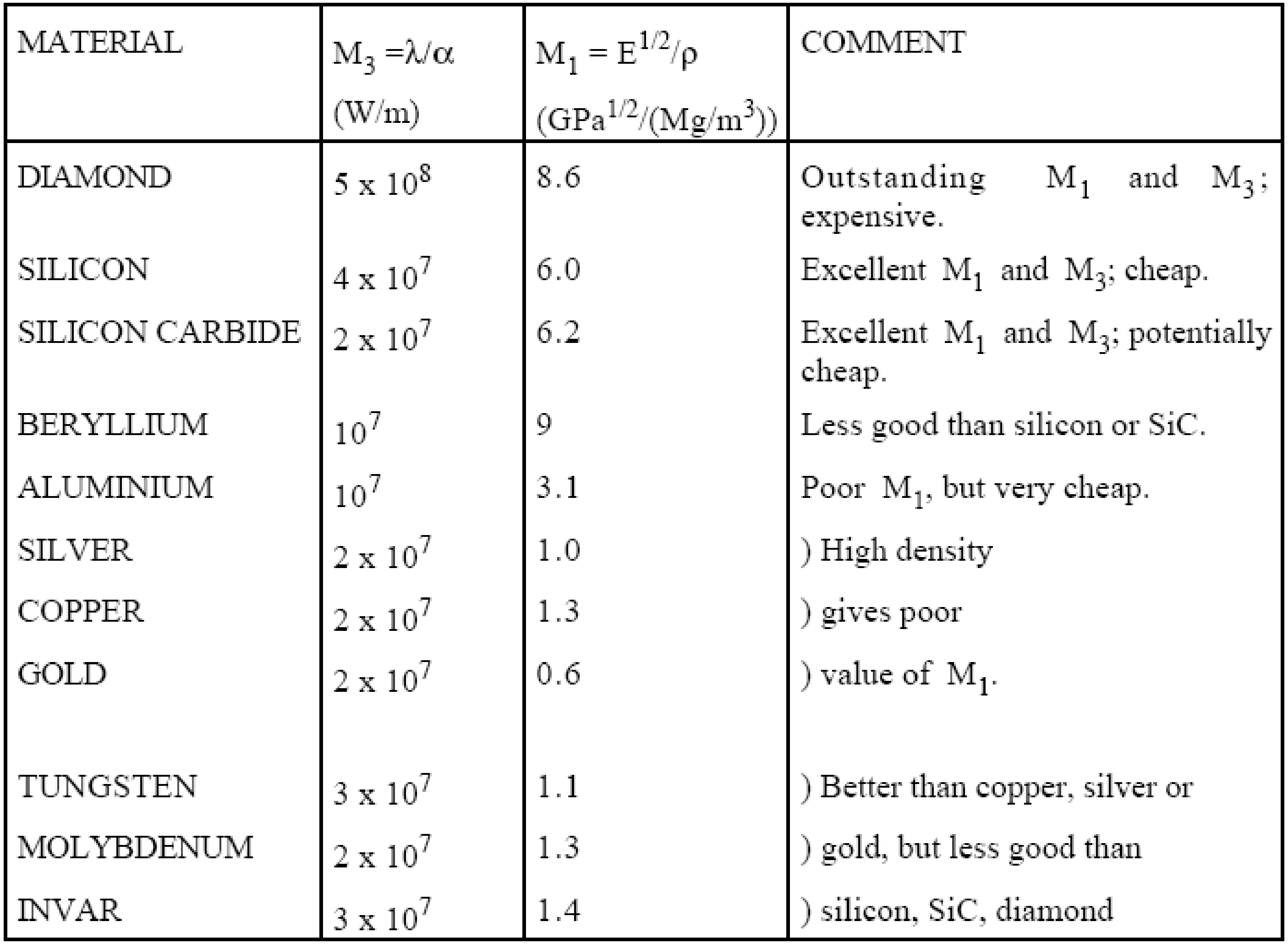
- A high value of this index will minimise the problem. Finally, of course, the device must not cost too much.

Materials for Precision Instruments

- Figure 4 shows the expansion coefficient, α, plotted against the thermal conductivity, λ. Contours show constant values of the quantity λ/α.
- A search region is isolated by the line $\lambda/\alpha = 10^7$ W/m, giving the short list of Table 2. Values of $M1 = E^{1/2}/\rho$ read from Figure 2 are included in the table.

Materials for Precision Instruments

- Table 2: Materials for Precision Instruments



MATERIAL	$M_3 = \lambda/\alpha$ (W/m)	$M_1 = E^{1/2}/\rho$ ($GPa^{1/2}/(Mg/m^3)$)	COMMENT
DIAMOND	5×10^8	8.6	Outstanding M_1 and M_3; expensive.
SILICON	4×10^7	6.0	Excellent M_1 and M_3; cheap.
SILICON CARBIDE	2×10^7	6.2	Excellent M_1 and M_3; potentially cheap.
BERYLLIUM	10^7	9	Less good than silicon or SiC.
ALUMINIUM	10^7	3.1	Poor M_1, but very cheap.
SILVER	2×10^7	1.0	) High density
COPPER	2×10^7	1.3	) gives poor
GOLD	2×10^7	0.6	) value of M_1.
TUNGSTEN	3×10^7	1.1	) Better than copper, silver or
MOLYBDENUM	2×10^7	1.3	) gold, but less good than
INVAR	3×10^7	1.4	) silicon, SiC, diamond

Materials for Precision Instruments

- Diamond is outstanding but practical only for very small devices.
- The metals, except for beryllium, are disadvantaged by having high densities and thus poor values of M_1 $E^{1/2}/\rho$.
- The best choice is silicon, available in large sections, with high purity. Silicon carbide is an alternative.
- Nano-scale measuring and imaging systems present the problem analysed here.
- The atomic-force microscope and the scanning-tunnelling microscope both support a probe on a force loop, typically with a piezo-electric actuator and electronics to sense the proximity of the probe to the test surface.

Materials for Precision Instruments

- Home applications include the mechanism of a video recorder and that of a hard disk drive which qualify as precision instruments; both have an actuator moving a sensor (the read head) attached, with associated electronics, to a force loop.
- The materials identified in this case study are the best choice for force loop.