# MATERIALS SELECTION IN MECHANICAL DESIGN

**Objectives**

* materials–selection procedure has been developed.
*use of *Materials Selection Charts*
*displaying material to find *performance indices*
*Optimization methods for simultaneous selection of both material and shape.

## INTRODUCTION

The performance of an engineering component is limited by the properties of the material of which it is made, and by the shapes to which this material can be formed. Under some circumstances a material can be selected satisfactorily by specifying ranges for individual properties. More often, however, performance depends on a combination of properties, and then the best material is selected by maximising one or more '**performance indices'**.

An example is the specific stiffness $E/\rho$ (E is Young's modulus and $\rho$ is the density). Performance indices are governed by the design objectives.Component shape is also an important consideration. Hollow tubular beams are lighter than solid ones for the same bending stiffness and I–section beams may be better still. Information about section shape can be included in the performance index to enable simultaneous selection of material and shape.

## THE PROCEDURE

### Performance Indices

**A *performance index* is a group of material properties which governs some aspect of the performance of a component** [1, 2]. They are derived from simple models of the function of the component, as illustrated by the following example.

Example1

***A material is required for a light, stiff beam**.

***The aim is to achieve a specified bending stiffness at minimum weight**.

* The beam has a length L and a square, solid, cross–section as shown in Figure 1a. The mass of the beam is

$$m = AL\rho \qquad (1)$$

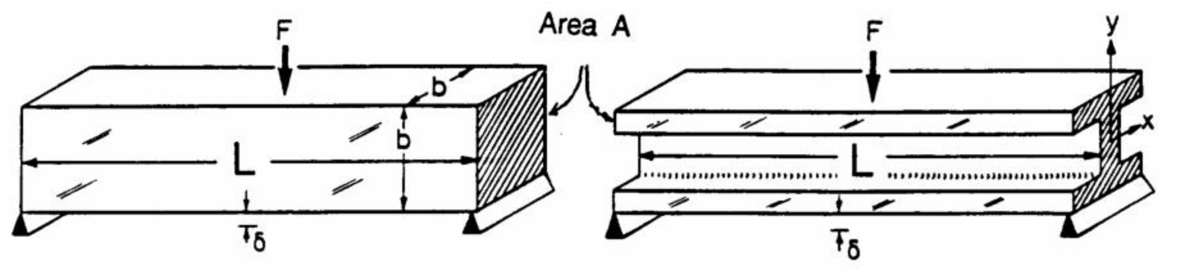


Fig. 1 (a) A square–section beam loaded in bending
(b) A beam of more complex cross section.

where **A** is the area of the cross–section and ° is the density of the material of which the beam is made. The stiffness **S** of a simply–supported beam with modulus **E**, second moment of area **I**, central load **F**, and central deflection ¢, is

$$S = F/\delta = (C_1 EI/L^3) \qquad (2)$$

with $C_1 = 48$ for 3-point bending. Other supports, or other distributions of load, change $C_1$, but nothing else. Assume that the beam has a square section, of side b. The second moment of area is

$$I = b^4/12 = A^2/12 \qquad (3)$$

The stiffness S and the length L are constrained by the design.
The area A is a ‘free’ variable that we wish to choose so as to minimize the mass, while meeting the constraints.

Substituting for I in equation (2) and eliminating A between this and (1) gives

$$m=[12S/C_1]^{1/2}\ (L)^{5/2}\ [\rho/E^{1/2}] \qquad (4)$$

The mass of the beam can be minimized (and performance maximized) by seeking the material with the largest value of the performance index

$$M_1=E^{1/2}/\rho \qquad (5)$$

The same performance index holds for square–section beams with any value of the design stiffness S, any boundary conditions and distributions of load (defined by $C_1$), and any length L.

The cross–section shape of the beam (like the I–section shown in Figure 1b) can be included in the performance index by introducing a dimensionless shape factor $\phi$, defined [3] by

$$\Phi=4\pi I/A^2 \qquad (6)$$

The value of $\phi$ measures the bending efficiency of the section shape.

For the solid section of Figure 1(a), $\phi \cong 1$; that for the I-section of Figure 1(b) is about 5.

Real I-sections have efficiencies, $\phi$ , as high as 40. The maximum value of $\phi$ is limited by manufacturing constraints or by local buckling of the component, and, for this reason, it can be considered to be a material property. **Shape factors** can also be defined for design against yield or fracture, and for shafts as well as beams. Using equation (6) in place of equation (3) to eliminate A in equation (1) gives the new index:

$$M_2=(\varphi E^{1/2})/\rho \qquad (7)$$

For a constant shape ( $\phi$ constant) the criterion reduces to the earlier one; the best selection is then the material with the largest value of $M_1$ (equation (5)). In comparing materials with different shapes, the best choice is that with the greatest value of $M_2$ (equation (7)).

## Material Property Charts

Material selection using performance indices is best achieved by plotting one material property (or mathematical combination of properties) on each axis of a *materials selection chart* [1,2]. In the example shown in Figure 2, the axes are Young's modulus and density. The logarithmic scales span a range so wide that all materials are included. When data for a given material class such as metals are plotted on these axes, it is found that they occupy a field which can be enclosed in a 'balloon'. Ceramics also occupy a field, and so do polymers, elastomers, composites, and so on. The fields may overlap, but are nonetheless distinct. Individual materials or sub–classes (like steels, or polypropylenes, PP) appear as little 'bubbles' which define the ranges of their properties. Hardcopy charts relating many mechanical and thermal properties are now available [1] (two appear in this article). Others can be constructed with the software described in a moment.

*The subset of materials with the greatest value of $M_1$ can be identified rapidly by taking logarithms of equation (5) ($\text{Log } E = 2 \text{ Log } \rho + 2 \text{ Log } M_1$), and

*plotting the resulting selection line of slope 2 on the chart. The construction is illustrated in Figure 2,

from which it can be seen that woods, fibre reinforced composites and some ceramics are the best choices for a light stiff beam with square cross–section.

When **section shape** is included in the selection criterion, (as in equation $M_2=(\varphi E^{1/2})/\rho$ (7)) woods become considerably less attractive, because they cannot be manufactured in thin sections with large shape factors, like metals.

SELECTION LINE

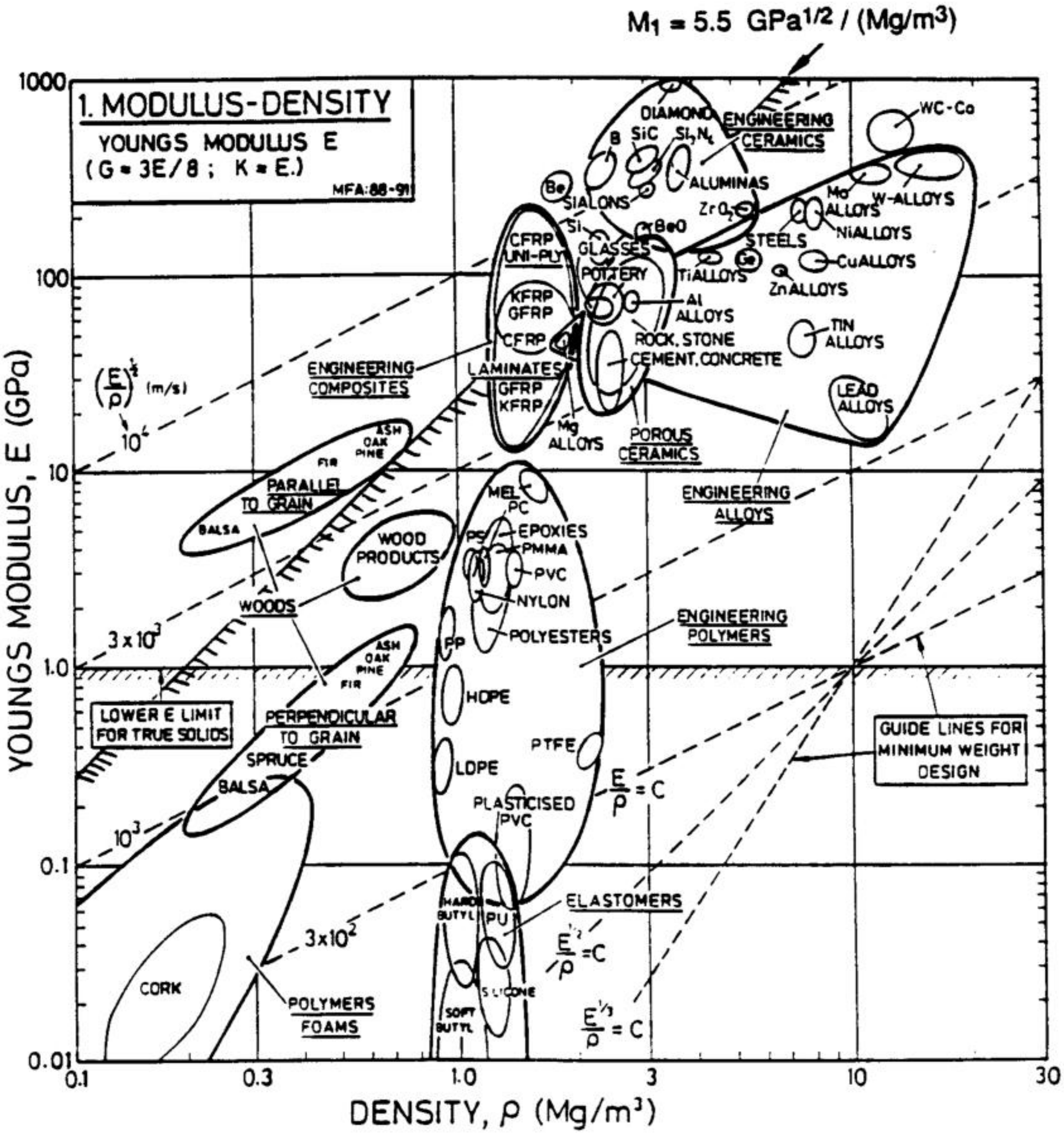


Fig.2 A modulus/density chart illustrating the selection of materials with high values of $M_1 = E^{1/2}/\rho$. Contours of constant $E^{1/2}/\rho$ appear as a family of lines of slope 2. Materials with $M_1$ greater than a specified value can be identified.

**IMPLEMENTATION IN SOFTWARE**

The 'Cambridge Materials Selector' (*CMS*) is a computer package consisting of a data base of material properties, a management system which recovers and manipulates the data, and a graphical user interface which presents the property data as material selection charts. The approach employs a number of novel features [4].

## CASE STUDIES 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, boats with oars appear in carved relief on monuments built in Egypt between 3300 and 3000 BC.

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**, 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

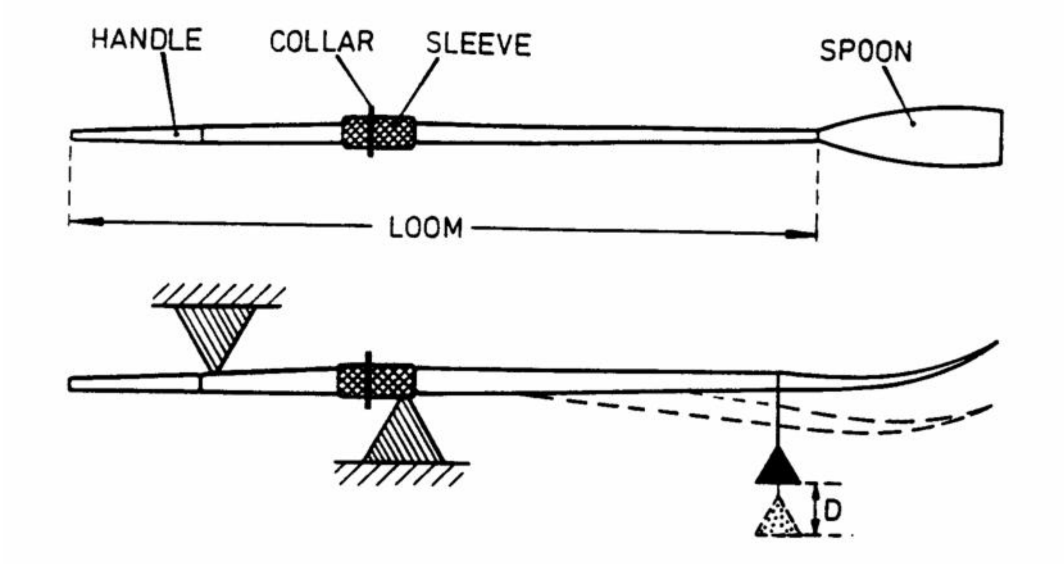

**Fig. 3 An oar, showing the components and the method of measuring the stiffness.**

Figure 3 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. 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 [5].

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**. The performance index we want was derived in earlier; it is $M_1=E^{1/2}/\rho$

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. 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

| COMMENT | M $(GPa)^{1/2}/(Mg/m^3)$ | MATERIAL |
|---|---|---|

| | | |
|---|---|---|
| Cheap, traditional, but not easily controlled.<br>As good as wood, more control of properties.<br>Cheaper than CFRP but lower M.<br>Good M but brittle and expensive | 5-8<br>4-8<br>3.5-5.5<br>4-8 | Woods<br>CFRP<br>GFRP<br>Ceramics |

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. Composite blades are a little lighter than wood, for the same stiffness. 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. At a price, of course: a CFRP oar costs about £300 ($450).

**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. 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 [6]. Elastic deflection is allowed, provided natural vibration frequencies are high.

What, then, are good materials for precision devices?

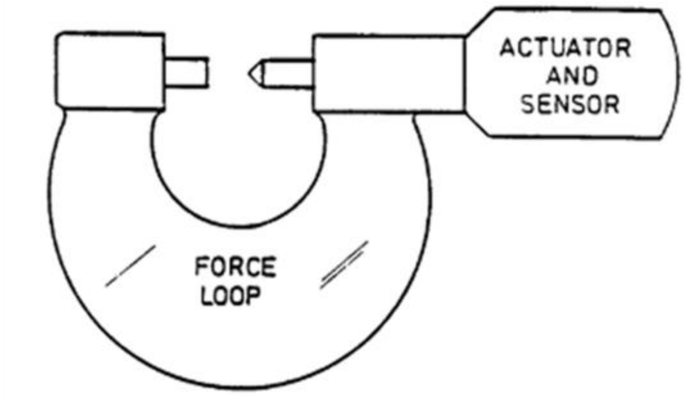


Figure 4. A precision instrument. It consists of a force loop, an actuator and a sensor

Figure 4 shows, schematically, such a device: it consists of a force loop, an actuator and a sensor; 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

$$q = -\lambda \, dT/dx \qquad (8)$$

where q is heat input per unit area, λ is the thermal conductivity and $\frac{dT}{dx}$ is the resulting temperature gradient. The strain is related to temperature by

$$\varepsilon = \alpha (T_0 - T) \qquad (9)$$

where α is the thermal conductivity and $T_0$ is ambient temperature, from which

$$d\varepsilon/dx = \alpha dT/dx = (\alpha/\lambda)q \qquad (10)$$

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

$$M_3 = \lambda/\alpha$$

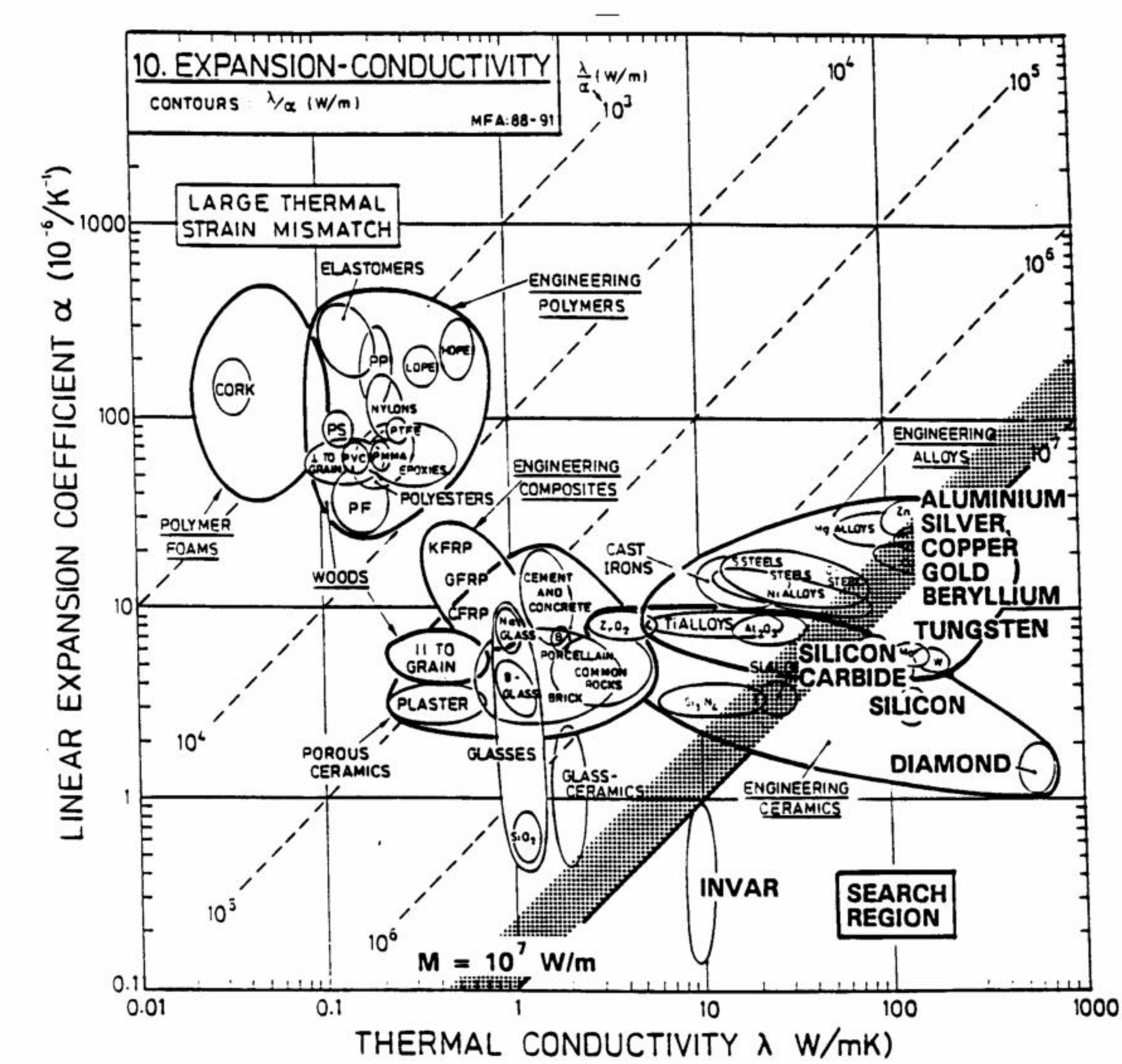


Figure 5. A Chart of thermal conductivity, , and expansion coefficient, , allowing selection of materials for the force loop of precision instruments.

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

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

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

Chart 10 (Figure 5) 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 λ/α= $10^7$ W/m, giving the short list of Table 2. Values of $M=E^{1/2}/\rho$ read from Chart 1 (Figure 2) are included in the table.

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

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. Closer to home, the mechanism of a video recorder and that of a hard disk drive 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.

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