Materials Selection in Mechanical Design

I. Mazínová and P. Florian

Abstract The contribution deals with material selection strategy in mechanical design. Material selection is tackled in four steps. The first step is *translation*—reinterpreting the design requirements in terms of function, constraints, objectives, and free variables. The second step is *screening*—deriving attribute limits from the constraints and applying these to isolate a subset of viable materials. The third step is *ranking*—ordering the viable candidates by the value of a material index, the criterion of excellence that maximizes or minimizes some measure of performance. The last step is *documentation*—seeking documentation for the top-ranked candidates.

Keywords Material selection strategy · Material property charts · Material indices

1 Introduction

There is no need to emphasize that materials play the key role during product life cycle. Material selection often determines success or failure of a product on the market. Therefore it should be taken into account in the early stages of the design process. However, having over 100,000 engineering materials to choose from makes this task significantly demanding. Fortunately, this process might be facilitated by using computer-aided-materials-selection software (CAMS) and materials charts.

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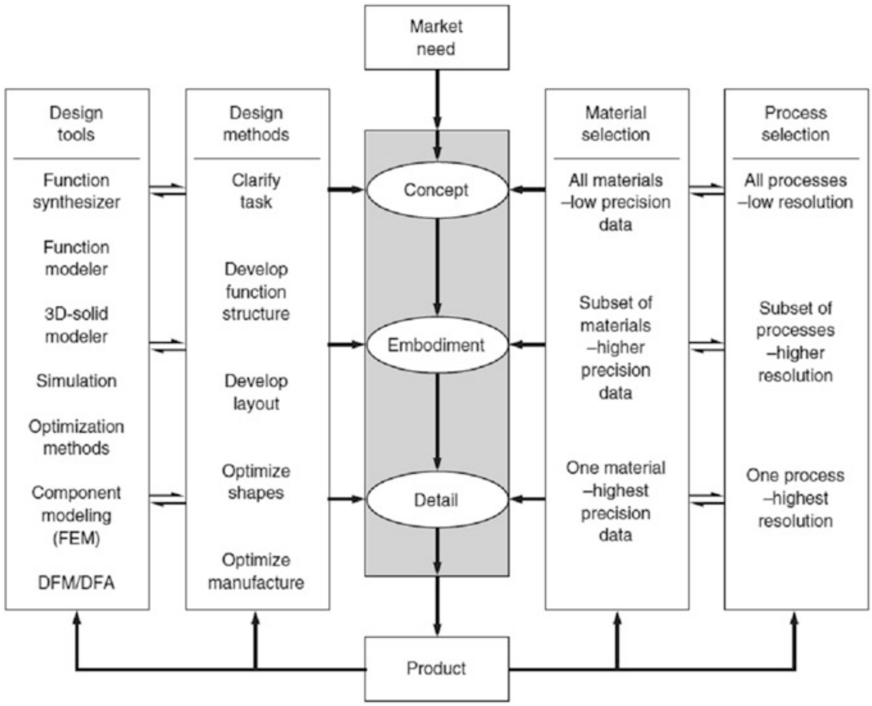

Fig. 1 Materials selection and design process (Dieter 2009)

Figure 1 present ideal relation between materials selection and design process. The earlier material selection is applied the more time can be saved in the later stages of the design process. It also shows that each following step in the design process needs more precise data. Manufacturing process selection is often overlooked but should be taken into account as well.

2 The Selection Strategy

2.1 Translation

Every component has to meet certain requirements. These requirements can be expressed by *functions*: carrying load, transmitting heat, damping vibration, etc. And the functions are satisfied with respect to *constraints* concerning dimensions, mass, cost, environment and so on. It is also vital to determine *objectives*; to make the component as cheap as possible, as light as possible, as stiff as possible, etc. There are also *free variables* which are not limited by any constraint but may influence overall performance. Summing functions, constraints, objectives and free

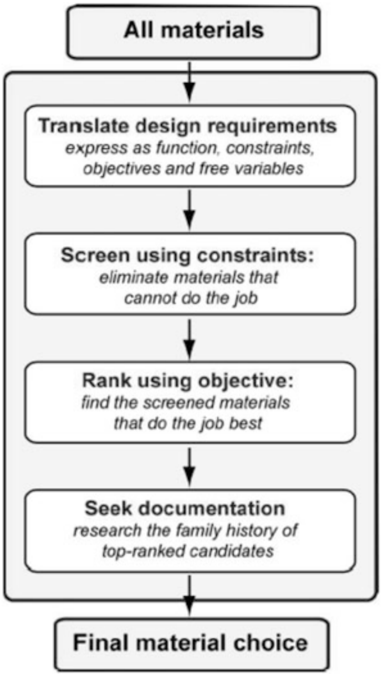

Fig. 2 The strategy for materials selection (Ashby 2011)

Table 1 Function, constraints, objective, and free variables

Function	• What does the component do?
Constraints	• What non-negotiable conditions must be met?
Objective	• What is to be maximized or minimized?
Free variables	• What parameters of the problem is the designer free to change?

variables together results in boundary conditions for material selection. The process of relating the boundary conditions to material properties is called *translation*. During translation designer's requirements are expressed by material attributes such as tensile strength, thermal conductivity, fracture toughness and so on. Ranges of values of each material attribute are also clarified in this step in order to implement them into computer-aided-material selection software (Fig. 2; Table 1).

2.2 Screening

Until this stage all materials were considered as potential candidates. But in this step the materials which do not comply with boundary conditions stated in translation phase are screened out. This process narrows down the list of potential

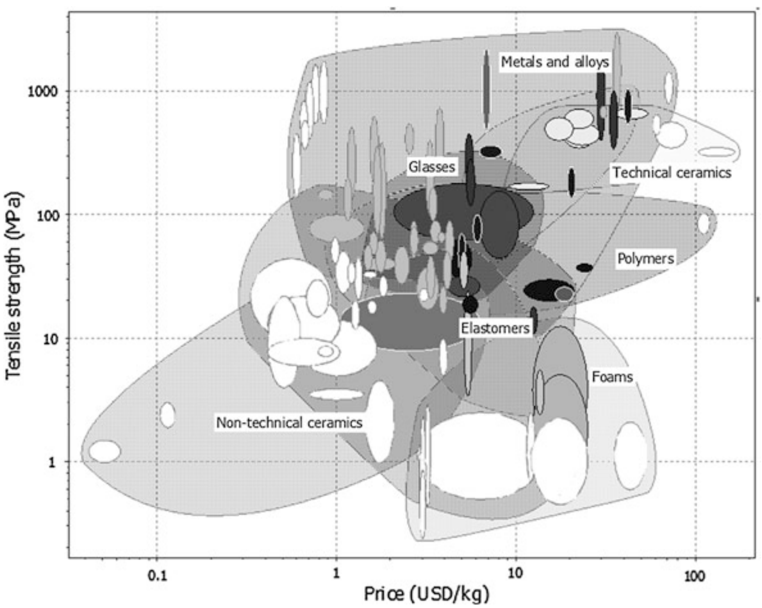

Fig. 3 Materials chart with applied constraints

candidates. Using CES EduPack (2012) in this step is convenient. Figure 3 contains white bubbles which represent unsuitable materials that do not meet attribute limits.

2.3 Ranking

Despite having smaller subset of materials after screening phase the list of potential candidates might be still too long to allow choosing a suitable material. The aim of the ranking stage is to put the remaining materials in order according to their performance. To do this material indices can be applied.

The performance of a structural element is determined by three things: the functional requirements, the geometry, and the properties of the material of which it is made. The performance *P* of the element is described by an equation of the form

$$\boldsymbol{P} = \left[\begin{pmatrix} \textbf{\textit{Functional}} \\ \textbf{\textit{requirements}}, \boldsymbol{F} \end{pmatrix}, \begin{pmatrix} \textbf{\textit{Geometric}} \\ \textbf{\textit{parameters}}, \boldsymbol{G} \end{pmatrix}, \begin{pmatrix} \textbf{\textit{Material}} \\ \textbf{\textit{properties}}, \boldsymbol{M} \end{pmatrix} \right]. \quad (1)$$

Performance of a material is given by one or more attributes e.g. the best materials for heat sinks are the ones with high value of heat conductivity λ, but

Table 2 Examples of material indices (Ashby 2011)

Function, objective, and constraints	Index
Tie, minimum weight, stiffness prescribed	$\frac{E}{\rho}$
Beam, minimum weight, stiffness prescribed	$\frac{E^{1/2}}{\rho}$
Beam, minimum weight, strength prescribed	$\frac{\sigma_Y^{2/3}}{\rho}$
Beam, minimum cost, stiffness prescribed	$\frac{E^{1/2}}{C_m \rho}$
Beam, minimum cost, strength prescribed	$\frac{\sigma_y^{2/3}}{C_m \rho}$
Column, minimum cost, buckling load prescribed	$\frac{E^{1/2}}{C_m \rho}$
Spring, minimum weight for given energy storage	$\frac{\sigma_y^2}{E_\rho}$
Thermal insulation, minimum cost, heat flux prescribed	$\frac{1}{\lambda C_p \rho}$
Electromagnet, maximum field, temperature rise prescribed	$\frac{C_p \rho}{\rho_e}$

ρ density; E Young's modulus; σ_y elastic limit; C_m cost/kg; λ thermal conductivity; ρ_e electrical resistivity; C_p specific heat

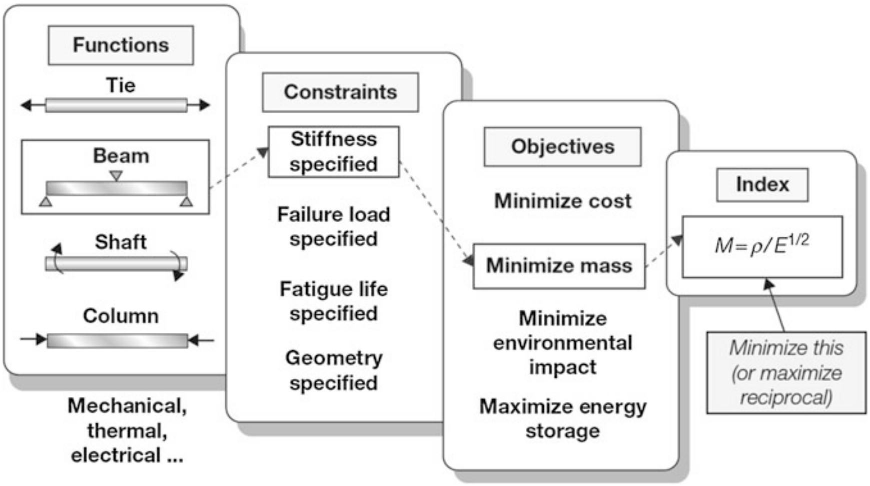

Fig. 4 Translation procedure and appropriate material index (Ashby 2011)

light, stiff ties need materials with high value of Young's modulus E and low values of density ρ as well. This means that materials with high ratio E/ρ would be very suitable for stiff ties. The ratio E/ρ is an example of *material index*. Material indices might be expressed by a single property (e.g. λ) or more properties (e.g. E/ρ). The key procedure of the ranking stage is searching maximum or minimum values of appropriate material indices in order to find the most suitable material for given application; however, the particular index should be derived already during translation (Table 2).

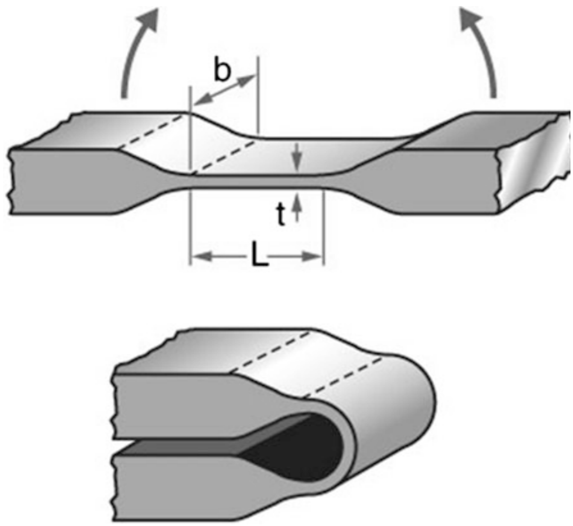

Fig. 5 Elastic hinges (Ashby 2011)

Figure 4 presents translation procedure and selection of an appropriate material index.

2.4 Documentation

In this final step only a few candidate materials should be on the list. It is important to gather precise data from materials suppliers to be able to conduct analyses and calculations since the data in the material database are not precise enough.

3 Case Study: Elastic Hinges and Couplings

Ligaments of elastic hinges must bend repeatedly without failing. A cap of a shampoo bottle is an example; elastic hinges are used in high-performance applications too, and are found widely in nature. Which materials make good hinges?

Translation: We consider the hinge (Fig. 5) for the lid of a box. The box, lid, and hinge are to be molded as a single unit. The hinge is a thin ligament that flexes elastically as the box is closed, as shown in the figure, but it carries no significant axial loads. Then the best material is the one that (for given ligament dimensions) bends to the smallest radius without yielding or failing (Table 3).

Table 3 Examples of material indices (Ashby 2011)

Function	Elastic hinge
Constraint	No failure, meaning $\sigma < \sigma_f$ throughout the hinge
Objective	Maximize elastic flexure
Free variable	Choice of material

Screening: However in this case, there is no need to screen prospective materials.

Ranking: So now we need to develop an index by which we can rank materials for their elastic flexure. When a ligament of thickness t is bent elastically to a radius R, the surface strain is

$$\varepsilon = \frac{t}{2R} \tag{2}$$

and—since the hinge is elastic—the maximum stress is

$$\sigma = E\frac{t}{2R}. \tag{3}$$

This must not exceed the yield or failure strength σ_f. Thus the minimum radius to which the ligament can be bent without damage is

$$R \geq \frac{t}{2}\left[\frac{E}{\sigma_f}\right]. \tag{4}$$

The best material is the one that can be bent to the smallest radius, that is, the one with the greatest value of the index

$$M = \frac{\sigma_f}{E}. \tag{5}$$

We can now apply performance index to set of prospective materials. We need the $\sigma_f - E$ chart again (Fig. 6). Candidates are identified by using the guide line of slope 1; a line is shown at the position $M = \sigma_f / E = 2 \times 10^{-2}$. The best choices for the hinge lie to the right of this line: They are all polymeric materials. The shortlist (Table 4) includes polyethylene, polypropylene, nylon, and, best of all, elastomers, though these may be too flexible for the body of the box itself. Cheap products with this sort of elastic hinge are generally molded from polyethylene, polypropylene, or nylon. Spring steel and other metallic spring materials (like phosphor bronze) are possibilities: They combine usable σ_f / E with high E, giving flexibility with good positional stability (as in the suspensions of relays).

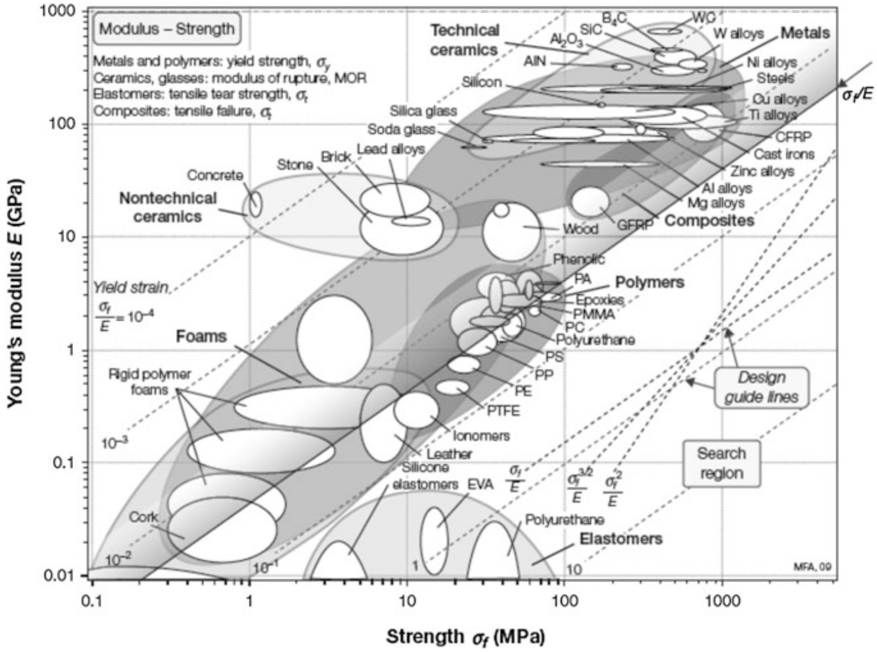

Fig. 6 Translation procedure and appropriate material index (Ashby 2011)

Table 4 Material for elastic hinges (Ashby 2011)

Material	M ($\times 10^{-3}$)	Comment
Polyethylene	32	Widely used for cheap hinged bottle caps, etc.
Polypropylene	30	Stiffer than Polyethylene; easily molded
Nylon	30	Stiffer than Polyethylene; easily molded
PTFE	35	Very durable; more expensive than PE, PP, etc.
Elastomers	100–1,000	Outstanding, but low modulus
High strength copper alloys	4	*M* less good than polymers; use when high tensile stiffness is required
Spring steel	6	

4 Conclusions

Material properties limit performance. We need a way of surveying them to get a feel for the values that design-limiting properties can have.

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