Materials selection

Material Science Practical - Semester 3

Objectives:
- To discover materials and selection methods;
- To learn how to use computer tools for material selection;
- To apply the selection procedure to case studies.

I. Introduction

In order to optimize the choice of materials for a particular industrial application, the procedure of selection of materials must be formalized so as to be as objective as possible.

The basic procedure for selection is to establish the link between material and function. A material has attributes: its density, strength, cost, resistance to corrosion, and so forth. A design demands a certain profile of these: a low density, a high strength, a modest cost and resistance to fatigue, perhaps. It is important to start with the full menu of materials in mind; failure to do so may mean a missed opportunity.

The three steps to follow are:

i) ***Ranking***: the procedure of selecting materials allows ranking the candidates by their ability to maximize performance. Criteria for ranking are derived from the design requirements for a component by an analysis of *function*, *constraints*, *objectives*, and *free variables*. The outcome of this step is a ranked short-list of candidates that meet the design requirements and that maximizes or minimizes the criterion of excellence, whichever is required.

ii) ***Screening***: examining the design requirements to identify the *constraints* that they impose on material choice. The choice is narrowed by screening-out the materials that cannot meet the constraints. As examples, the requirement that ''the component must function in boiling water'', or that ''the component must be transparent'' impose obvious limits on the attributes of maximum service temperature and optical transparency that successful candidates must meet.

iii) ***Documentation***: For materials having passed the first two steps, seeking supporting information for the top-ranked candidates, exploring aspects of their past history, their established uses, their behavior in relevant environments, their availability and more until a sufficiently detailed picture is built up that a final choice can be made.

The selection procedure follows a hierarchical approach, from general to more specialized: families (metals, ceramics, polymers, etc.), classes (steel, light alloys, etc.), subclasses (1000, 2000, etc.) and members (5083 H2, H4 5083, etc.) of materials (see Figure. 1).

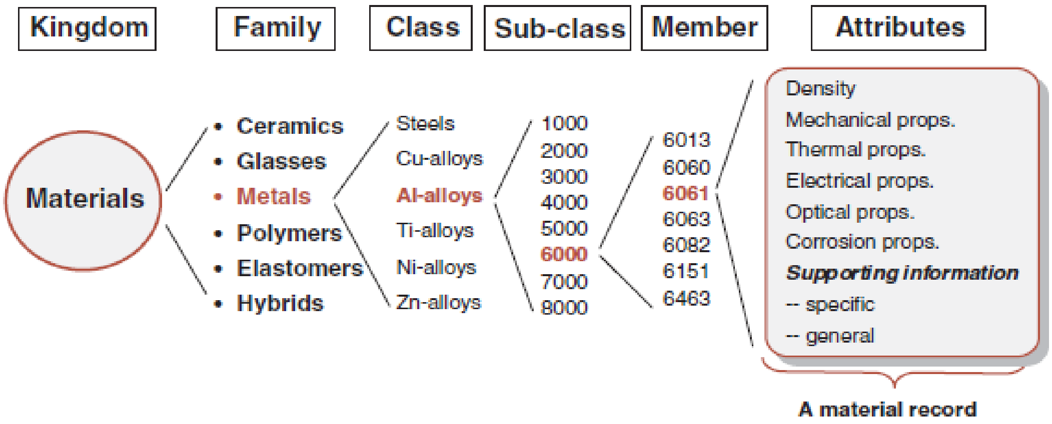


Figure 1. The taxonomy of the kingdom of materials and their attributes. Computer-based selection software stores data in a hierarchical structure like this. (Source "Materials Selection in mechanical design" M. F. Asbhy, Ed)

Finally, note that the materials selection is an iterative procedure, the results of the classification list may suggest a posteriori corrections (solution not matching the selection criteria; too many solutions equivalent; need to refine the query; etc.).

This practical session is an introduction to the methods for selecting materials, and the use of CES support software. For this, we will focus on several case studies illustrating the screening methods. They are deliberately simplified to avoid obscuring the method under layers of detail.

As such, we will not have time to deal in depth with multiple-criteria selection, multi-material selection, choice of assembly methods, the use of volume or surface treatments to change material properties, and in general we will not consider the implementation method that would otherwise be a fundamental phase in the materials selection procedure.

II. Rating materials performance: low cost rigid column

In this section we will detail the method for determining the *performance index* of a material, conceived as a combination of its properties, in order to objectively assess the best match between the property-profile of the material and that required by the design. For this, we consider the simple example of the selection of materials for making a rigid column at low cost. The columns support compressive forces (the legs of a table, the columns of Parthenon, etc.). We wish to build a column with a fixed height h, capable of supporting an imposed load F without buckling, and as cheap as possible (see Figure 2).

A. Procedure

1. Function: what is the *imposed* function of the object?

2. *Objective*: which aspect would we like to maximize or minimize?

3. *Parameters*:

- *Fixed*: which parameters are imposed (geometry, function)?

- *Adjustable*: which parameter can we adjust?

- *Material:* What are the properties of the material considered?

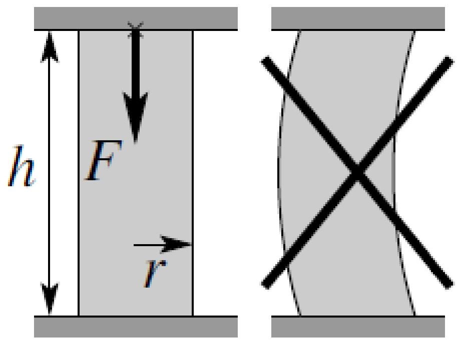


Figure 2. Scheme of a column. The elastic buckling is the tendency of a column stressed in longitudinal compression to flex and thus deform in a direction perpendicular to the applied force.

B Determining the performance index

4. Equations:

a) write the equation defining the *objective* introducing the price per kilogram C_m and the density ρ;
b) the critical force causing the buckling of a circular section column of height h, radius r and Young's modulus E, is written: $F = \pi^3 E r^4 / 4h^2$; using this equation related to the *function* of the object, express the adjustable parameter as a function of the other parameters of the equation.

5. Performance function:

In the equation defining the *objective* (step 4.a), replace the adjustable parameter by its expression obtained in step 4b); then separate, in the equation of the objective, the fixed parameters (geometry, function) from the material properties;

6. Performance Index: from the material properties, deduce the performance index.

C Classification of materials

A convenient way to present the material properties is to plot them in "material property charts". These are logarithmic diagrams, which represent a quantitative property on each axis. Different types of materials are represented by bubbles whose size reflects the dispersion of the properties of a set of materials.

CES software, using generic databases, allows, among other things, to draw such charts. Plotting equi-performant lines on these maps allows ranking the materials relative to a given performance index.

NB: to use CES program follows the instructions given. These must be consulted before answering the following questions.

7. Axes: Knowing the expression of the performance index, choose the associated coordinates of the axes O_x and O_y in the chart of properties;

8. Slope: What will be the slope of the equi-performant lines on this chart? Will the best performing materials be located on the highest or lowest lines (justify)?

9. List: Determine a ranked list of 5 candidate materials to make the column ;

10. Documentation: Relying on the documentation available in CES, discuss the advantages and disadvantages of the various candidate materials in the context of the construction of a building; for this purpose, the information gathered (thermal properties, environmental durability, forming processes, environmental properties, aesthetic, etc.) will be organized in a comparative table.

III A low-cost electrical cable

We wish to realize at the lowest cost an electric cable. To limit electrical losses, the electrical resistance of a kilometer long cable is imposed to be less than a critical value R_0. Furthermore, the cable must be capable of withstanding a tensile force T_0 without breaking. The electrical resistance of a wire of section S, length L and resistivity ρ_e is given by: $R = \rho_e L/S$.

1. We initially consider the requirement of *mechanical strength*: determining the function, objectives and parameters of the problem;

2. Following the approach outlined in Section II, determine first the performance index;

3. Using the CES software, establish a list of 5 candidate materials ranked by performance index (describe the procedure);

4. Repeat steps 1 to 3, considering now the electric resistance query (formulate the associated performance index, which we will call I_2);

5. The requests are contradictory, no material looks optimal. Which solution will be adopted in practice to overcome this difficulty?

IV Materials for oars

Credit for inventing the rowed boat seems to belong to the Egyptians. Rowing was an established university sport in England but real stimulus for the development of boat and oar came in 1900, with the advent of rowing as an Olympic sport. Since then, the search for technical solutions for high performance rowing has taken off.

Mechanically speaking, an oar is a beam, loaded in bending (see figure 3). It must be strong enough to carry, without breaking, the bending moment exerted by the oarsman, it must have a stiffness to match the rower's own characteristics, and—very importantly—it must be as light as possible. Meeting the strength constraint is easy. Oars are designed on stiffness, such as to give a specified elastic deflection under a given load (see Appendix 1). There are other obvious constraints. Oars are dropped, and blades sometimes clash. The material must be tough enough to survive this, so brittle materials (those with a resilience G_{Ic} [1]less than 1 kJ/m^2) are unacceptable. In order to limit the price of the oar we also impose that the mass material cost must be less than 100 EUR/kg. These criteria will allow us to filter materials before the classifying step (for this you can use a properties chart representing resilience as a function of price, on which you can select (*use the box selection option*) satisfactory resilience and price values.

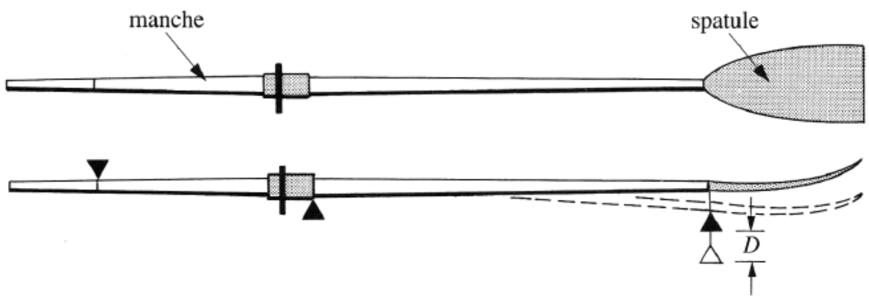


Figure 3. Scheme of an oar

1. Determine function, objective and parameters;

[1] The G_{Ic} resilience is connected to the toughness K_{Ic} and Young's modulus E by the relationship $G_{Ic} = K_{Ic}^2/E$; in this expression, when the K_{Ic} is expressed in $MPam^{1/2}$ and the Young's modulus in GPa, the resilience is expressed in kJ/m^2.

2. Following the approach outlined in Section II, determine the performance index associated with this requirement (physical relationships on the bending behavior of beams are available in the Appendix);

3. Using the CES software, establish a ranked list of 5 materials by optimizing the performance index, compatible also with the requirements for resilience and cost, (describe the various stages of the procedure used).

4. Among the materials from this list, which one helps to produce the lightest oar, and which one the cheapest? Calculate the mass and price ratio between these two materials. Comment.

V Materials for heat exchangers

Heat exchangers take heat from one fluid and pass it to another (Figure 4). A key element in all heat exchangers is the tube wall or membrane that separates the two fluids. It is required to transmit heat, and there is frequently a pressure difference across it, which can be large. We know that the fluid inside the tube is hot (T >150 °C) and contains chloride ions (sea water). We would like to maximize the heat flow avoiding the plastic deformation of the tube that has a fixed radius r. The heat exchange is given by: $Q=\lambda\Delta T/e$, where λ is the thermal conductivity of the tube, $\Delta T=T_1-T_2$ is the temperature difference between the fluid 1 and the fluid 2, and *e* is the thickness of the tube wall. The tensile stress in the tube due to the pressure difference is: $\sigma= r\Delta P/e$, where $\Delta P=P_1-P_2$ is the pressure difference between fluid 1 and fluid 2.

1. Establish the list of requirements: determining the function, objective and parameters.

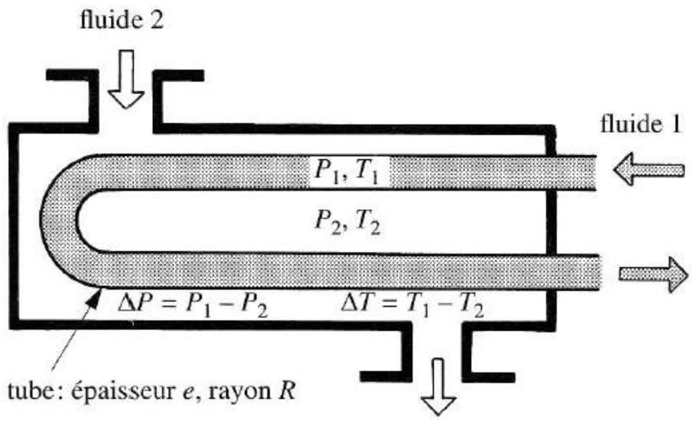


Figure 4. Scheme of the heat exchanger

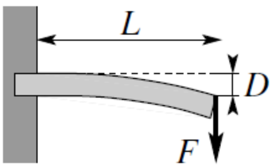
2. Following the approach outlined in Section II, determine the performance index.

3. Using the CES software, rank the materials by performance index (describe the procedure). Which class and subclass of materials would be most suited?

4. Now do a finer choice of materials (for this, use the Database Level 3) taking into account the particular operating conditions (temperature and water salt[2]), and imposing a maximum price of 3 EUR/kg. Retain a list of 3 candidate materials by (describe the different stages of the procedure used).

Appendix 1

Bending Beam



$$\frac{D}{F} = \frac{L^3}{EJ}$$

$J = a^4/12$

$J = \pi r^4/4$

D is the elastic deflection and E the Young Modulus

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[2] As limits, use *Water (salt) = Excellent* in the category *Durability*: *fluids and sunlight*.