Short communication

Innovation and sustainability in mechanical design through materials selection

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Abstract

Materials selection is a difficult and subtle task, due to the immense number of different available materials. Dealing with such exhaustive information was made possible through the systematization of the materials by their properties. Systematization provides enlarging the classical list of materials and offers new possibilities, facing innovation and sustainability.

A practical example concerning the selection of materials to substitute poly vinyl chloride (PVC) in automobile interiors, is studied. Substitution intends avoiding health damage and environmental burden due to PVC, meeting, at the same time, the innovation quises and the sustainability exigencies.

Selection was made by applying the methodologies developed by Ashby and co-workers. Natural materials cork and wood were selected.

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1. Introduction

Trying new materials, creating new shapes, optimizing or developing new fabrication processes and evaluating the performance of the new products, are challenges posed to designers.

Materials evolve through the development of new structures, offering new capabilities and enabling innovative design, or redesign, in order to obtain the product’s best advantages. Faced from this side, design concerns the creation of products and components, by establishing the relations between the materials and the processes to shape them, always under the flag of environmental friendliness.

Designing a product is an iterative process, which begins with the formulation of a need and follows with the definition of a function, the specification of a shape, the selection of a material, the option for a fabrication process. These steps are not independent and the optimization of their mutual interactions leads to obtaining the product best performance. The fabrication, use and disposal of the products carry environmental loads, which are never completely recoverable and cause accumulated damage. Eco-problems do rise, which are partially solved by an adequate selection of materials and processes; materials with low energy content minimize environmental burden [1–3].

In the overall design process the selection of materials is fulcral. Designers are presented with an endless choice of materials and manufacturing techniques and the making of decisions, traditionally based on experience, is nowadays achieved by means of selection criteria supported on systemized information. Systematization
allows capturing the materials most important features, as well as the rapid retrieval of a large amount of information, which promotes new possibilities and innovation.

Engineering materials are conventionally grouped in six broad classes (Fig. 1), which subdivide in sub-classes and families, according to the ranges of the attributes. Considering the attributes and two of them plotted one against the other, charts are produced (Fig. 3), which offer a quick and concise search. Data-bases as charts and computer programs, were produced by many authors [4–6]; in the present study, the charts and methodologies developed by Ashby and co-workers are followed.

Charts are graphical representations of material properties, where the data corresponding to the different classes tend to form clusters and the sub-ranges associated with the classes appear as bubbles inside the clusters.

For material selection, designers establish the set of the required properties and seek the materials, by comparing the properties across all the classes. Charts are consulted [1,3,7] to find the materials which offer the best match. These are evaluated for the ability to perform the function; the material(s) that maximizes the performance is selected. During the evaluation the material constraints are analyzed in detail: properties which are necessary, may not be sufficient to assure the product good performance; materials have their own strengths and limitations, which the designer must be aware.

2. Materials selection

Design involves creative thinking supported by systematic procedures, which help in making rational choices, instead of relying on experience. Procedures [1,4,5] comprise the definition of the function, in order that the object may satisfy the need, the development of a model, where the analysis of alternative concepts take place, and the selection of the materials and fabrication processes. Selection involves evaluating the two-way interactions between function, material, shape and fabrication process (Fig. 2). The need creates the function, the function dictates the choice of both the shape and the material; the material is selected considering the shape and the fabrication process; the fabrication process depends on the shape, the size and the precision and determines the cost.

The best solution is attained by calculating the property limits for the working conditions, which provides separating the materials that satisfy the conditions from all the others. The candidate materials are ranked by their ability to maximize the performance(s), which is measured by the material indices, given by a combination of the required properties. Charts help in selection: the materials are grouped by the sought properties and the plot of the line that establishes the property limits (guideline) allows isolating and visualizing the set of the candidate materials (Fig. 3).

The selection process goes beyond production: performance is always under evaluation and, in case of failure, the analysis of the causes gives relevant information; failure is seldom eliminated by re-designing the product or selecting the materials.

The economical viability of products is also evaluated, taking into account the material, the fabrication process, the size of the production run and the components added value. When the products are considered viable, a prototype is produced and assessed for the performance in the market, before the full scale production is established. At this point designers keep improving the product, making it cheaper and searching for its competitive position in the market.

3. Experimental application

A material is searched for substituting poly vinyl chloride (PVC) in automobile interiors [11].
3.1. The need and the function

The need: ‘materials which offer good alternative to PVC, in automobile interiors’. The function: ‘perform in covering automobile interior panels’.

3.2. The model

Automobiles are exposed to weather, being heated, by direct exposition to the sunshine, and being cooled, by the heat extracted during the night. These variations of temperature must not affect the performance of the components.

An essential of the materials that cover automobile interior panels is to minimize the heat flow through them (maximize thermal insulation) and the effect of the heat in the shape (minimize thermal distortion); another essential is the environmental impact, which is to be minimized, by opting for materials with low energy content.

Under the reasons above, the following objectives were established: (1) good heat insulation under heating or cooling; (2) low thermal distortion under heating or cooling; (3) low environmental impact under fabrication and disposal. The material main constraints are referred below, in the design requirements summary.

Design requirements [1]:

<table>
<thead>
<tr>
<th>Function</th>
<th>Covering automobile interior panels (heat non-storing material)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objectives</td>
<td>Maximize insulation (index $M_1$)</td>
</tr>
<tr>
<td></td>
<td>Minimize thermal distortion (index $M_2$)</td>
</tr>
<tr>
<td></td>
<td>Minimize environmental impact (index $M_3$)</td>
</tr>
<tr>
<td>Constraints</td>
<td>Lightness, resistance to use, good touch, easy to clean, ‘low’ cost (cost is a negotiable constraint)</td>
</tr>
</tbody>
</table>

3.3. Material indices and property limits

The thermal insulation index, $M_1$, is related with the thermal conductivity ($\lambda$) and thermal diffusivity ($a$) of the material.
Thermal insulation is the property that refers to the material heat content per unit area (Q [kJ/m²]), when heated through a temperature interval (ΔT [K]). Q is related with the thickness of the component (w [m]) and the material density (ρ [kg/m³]) and heat capacity (Cₚ [J/kg °C]), by the expression:

\[ Q = w \cdot \rho \cdot C_p \cdot \Delta T. \] (1)

The volumetric specific heat, ρ·Cₚ, is closely related to the material properties which govern the flow of heat through the material at steady state (thermal conductivity, λ [W/mK]) and the transient heat flow (thermal diffusivity, α [m²/s]), by the expression ρ·Cₚ = λ/α.

The diffusivity (α), the thickness (w) and time of exposure (t [s]), are related by the expression w = √(2αt). Making the substitutions in expression (1), we get the relation between the heat content and the material insulation index \( M_1 = λ/\sqrt{α} \).

\[ Q = \sqrt{(2t)} \cdot \Delta T \cdot (λ/\sqrt{α}). \] (2)

The heat capacity is minimized by the materials with the lowest values of \( M_1 \). Assuming the weather conditions are the thermo amplitude of 30 °C, during 8 h (3 × 10⁴ s), the property limits are defined by the guideline Q = 6 × 10⁷ (λ/√α). The line plot, on the respective chart, is given in Fig. 3, illustrating the separation of the candidate materials, situated below the line. These are summarized in Table 1.

The thermal distortion index, \( M_2 \), is related with the coefficient of expansion (α) and the conductivity (λ) of the material. Materials with low thermal distortion present large index values.

Thermal distortion, measured by the linear expansion under heating (x [K⁻¹]), is given by x = dℓ/ℓ·dT, where ℓ is the linear dimension of the object.

The candidate materials assume values of index \( M_2 = λ/α \), obtained in Chart 10 [1], and given in Table 1. The environmental impact index, \( M_3 \), is calculated from the materials energy content (Table 16.1 in [1]). The energy content is expressed per weight, q [J/kg], or per volume, p·q [J/m³]. The candidate materials assume values of index \( M_3 = ρ·q \), obtained in Chart 18 [1], and given in Table 1.

### 3.4. Selection

Considering the ranking of the candidate materials by the indices \( M_1 \), \( M_2 \) and \( M_3 \), it comes out that the materials that maximize index \( M_1 \) and minimize indices \( M_2 \) and \( M_3 \) are cork and wood (Table 1). These appear as the best materials to satisfy the objectives (and the constraints), offering a gain in insulation, as well as superior possibilities for recyclability and re-use. Other properties and the way they affect the material performance in the function, must be carefully evaluated.

### 4. Cork and wood properties

Cork and wood present high natural variability, due to genetic and environmental reasons. Other properties, such anisotropy and sensibility to environment and age, oppose to the remarkable advantages, which are cost and environmental friendliness (see Table 2).

The materials attributes are mainly related with the chemical composition and the structural arrangement. The chemical composition of cork and wood [8], involves the same basic components, although in different proportions: cork is rich in suberin, which does not exist in wood; wood is rich in cellulose, which exists in a low proportion in cork. These aspects bring relevant differences in the material behavior to industrial applications. Suberin is mainly composed by fatty organic acids, with low weight, which confer the cork impermeability and low density; cellulose is mainly composed by chains of high-molecular-weight linear polymers, which confer

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight (%)</th>
<th>Wood</th>
<th>Cork (raw)</th>
<th>Cork (amadia)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>40–50</td>
<td>10.1</td>
<td>9.1</td>
<td></td>
</tr>
<tr>
<td>Lignin</td>
<td>25–30</td>
<td>22.4</td>
<td>24.0</td>
<td></td>
</tr>
<tr>
<td>Hemicellulose</td>
<td>20–25</td>
<td>9.9</td>
<td>10.9</td>
<td></td>
</tr>
<tr>
<td>Extractives</td>
<td>0–10</td>
<td>16.9</td>
<td>14.2</td>
<td></td>
</tr>
<tr>
<td>Ashes</td>
<td>&lt;1</td>
<td>0.9</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Suberin</td>
<td>–</td>
<td>35.2</td>
<td>39.4</td>
<td></td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>40–1230</td>
<td>120–200</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 1: Materials for automobile interiors; material indices \( M_1 \) (efficient insulation), \( M_2 \) (thermal distortion) and \( M_3 \) (low energy content).*

<table>
<thead>
<tr>
<th>Material</th>
<th>( M_1 = \lambda/\sqrt{α} ) (W/m³·K)</th>
<th>( M_2 = \lambda/α ) (W/m)</th>
<th>( M_3 = q·ρ ) (GJ/m³)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porous ceramic</td>
<td>3 × 10⁻³–3 × 10⁻²</td>
<td>10⁻⁵–10⁰</td>
<td>10–200</td>
<td>Eliminated by brittleness</td>
</tr>
<tr>
<td>Elastomers</td>
<td>10⁻¹–10²</td>
<td>8 × 10⁻⁴</td>
<td>5–10</td>
<td>Best for short-term insulation</td>
</tr>
<tr>
<td>Solid polymer</td>
<td>10³</td>
<td>10⁻⁴</td>
<td>60–300</td>
<td>Good choice</td>
</tr>
<tr>
<td>Polymer foam</td>
<td>3 × 10⁻³–3 × 10</td>
<td>10⁻³</td>
<td>10–100</td>
<td>Very low contact pressure</td>
</tr>
<tr>
<td>Cork</td>
<td>3 × 10⁻²–3 × 10</td>
<td>5 × 10⁻⁴</td>
<td>1–3</td>
<td>Lower ( M_1 ) and ( M_2 )</td>
</tr>
<tr>
<td>Wood</td>
<td>3 × 10²</td>
<td>2 × 10⁻³ (L) 10⁵ (J)</td>
<td>1–3</td>
<td>Dimension instable; good in weight</td>
</tr>
<tr>
<td>Glass fiber</td>
<td>10⁻⁵</td>
<td>10⁻⁶</td>
<td>(30–90)</td>
<td>Eliminated by brittleness (in torsion)</td>
</tr>
</tbody>
</table>
the wood higher density and dependence on humidity. The other organic components, in particular lignin, act as binding compounds, conferring elasticity and compressibility to the materials.

In what concerns the structural arrangement, both materials are cellular structured, which tributes them lightness and ability for efficient insulation to heat, sound and mechanical vibrations.

The cellular morphology and arrangement, however, are different. Cork presents hollow, straight sided pentagonal or hexagonal prismatic cells with dimensions generally below 50 µm (Fig. 4(a)); wood presents hollow, elongated spindle-shaped cells, arranged parallel to each other along the trunk of the tree. Properties as strength and shrinkage assume different values in wood, depending on if the cut direction is parallel or perpendicular to the radius (Fig. 4(b), [1,9,12]).

5. Conclusions

Under the objectives established, cork and wood were the selected materials. Main advantages are related with the environmental aspects: easy recyclability, re-usability and health friendliness.

Cork and wood varieties of tones and textures may be successfully explored in decoration, conferring to automobile interiors a comfortable and fresh look and to the steering wheels and gear knobs, which are handled pieces, a gain in ‘good touch’ and heat insulation.

Cork offers unique properties, which make it very attractive for industry; in addition, the cork-tree offers the advantage of remaining the only tree whose bark can regenerate itself after harvest, leaving the tree unharmed; it is truly a renewable, environmentally friendly resource, which finds in Portugal its major producer, in the world [10].

Woods, in particular the heat-treated ones [12] are considered a material for the future. Heat-treated wood offers the advantages of being ecological and requiring ecological methodologies of manufacture.

References


Fig. 4. Scanning electron image of cork (a) and wood (b) cellular structure (⊥ to radius).