Projetando com Leveza, Resistência ao Calor e Durabilidade: Seleção de Materiais aplicada ao Design.

The Role of Materials Selection on Designing for Low Weight, Heat Resistance and Durability.

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Palavras-chave: Design, Seleção de Materiais, Desenvolvimento de Produtos

Resumo: Designers de produtos consideram, além dos aspectos funcionais e estético-culturais, o desempenho e o projeto mecânico. Este artigo apresenta e discute algumas propriedades de materiais importantes para o design, como módulo elástico, tensão de escoamento, dureza e temperatura máxima de serviço. Três objetivos são apontados: redução de peso, desempenho térmico e durabilidade.

Keywords: Design, Materials Selection, Product Development

Abstract: Product designers are concerned not only with the aesthetic dimensions of their work but with performance and engineering design as well. This paper presents and discusses some material properties of importance for design, that is, elasticity modulus, tensile strength, hardness and maximum operating temperature. Three design objectives are presented and discussed: minimum weight, thermal performance and product durabilityt.

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I. Introduction

Designers are perfectly aware that besides having to fulfil aesthetic requirements, a successful product must be functional, in the engineering sense, and that most of the times this functionality is strongly related to the correct choice of construction materials. In order to operate within this context, the knowledge of materials properties must be combined with a complete description of the demands made by the environment and working conditions. The coupling between these two bodies of information is greatly facilitated by a methodology denominated Materials Selection (MS), which nowadays makes part of the curriculum of a number of engineering courses.

From the materials engineer point of view, understanding materials is equivalent to establish theoretical or experimental correlation between properties on one hand, and microstructure and chemistry of the material on the other. New materials, improvement of the existing ones, less environmental damage, better productivity and lower costs are the results of intense R&D activity of materials engineers and scientists. These efforts have been quite successful: today the consumer can choose among some 50,000 - 60,000 different materials and an enormously wide range of properties. Also, Materials Science and Engineering is a well established academic and industrial body of knowledge which has been channelled into a number of Handbooks [1, 2, 3] and web sites [4, 5], meaning that between the users and all kind of materials' properties (mechanical, thermal, electrical, magnetic, and so forth) there are only a few pages and two mouse clicks
A common assumption regarding materials properties is that they are necessary only when dealing with mechanical design. Thus, bending strength is important for a connecting rod but does not need to be taken into account when designing, say, a new line of cutlery. This is a consequence of the disproportionate importance given to the aesthetic character of a 'design' product, as if it would never be submitted to load, heat, wear, corrosion, ultra-violet radiation, etc. Thus, a prize-winning new line of cutlery will be useless if forks and spoons bend or crack easily when in use. Therefore, besides the aesthetic aspect, designers must take material properties and working conditions into consideration in order to comply with the functional requirements of their work.

A short definition of 'good' material could be: 'the one which better fits properties to requirements'. This coupling is the task of Materials Selection (MS), whose concepts, principles and techniques are described in a number of books and articles [6, 7, 8, 9, 10]. In the example given above MS will be based on tensile strength, a not very complicate issue since there is an enormous choice of that property. However, structural integrity is only one aspect among many others: low weight, good surface finish and corrosion resistance are other functional properties which must be analyzed simultaneously. Finally, the selection of Manufacturing Processes must be included in all MS procedures since any chosen solution must be realized by a manufacturing technique suitable to both material and shape [11].

This paper intends to emphasize the importance of MS for industrial design practice. It begins with a review of MS concepts and principles and applies them to three important technical requirements of which either one, two or all three, pervade most product design: Designing for low weight; Designing for heat resistance; Designing for durability.

II. Design Requirements in Material Selection

II.1. Designing for low weight

If one analyzes two different products, for instance, an expensive watch and a vacuum cleaner, it is apparent that low weight may be a liability for the watch since it evokes cheapness (of course, if the marketing appeal is modernity, youth, etc., lightness will be an asset, as for titanium and aluminium high-tech watches). However, lightness is a mandatory requirement for the vacuum cleaner, as it is for most industrial products.

Low weight or low mass is associated to low density materials. Therefore, comparing the mass of, say, beams manufactured from different materials one would expect that their weight ratios would scale with their respective materials' density ratios. However, this is rarely observed. In fact, in almost any real situation, the product or component has to withstand mechanical loads, therefore the volume, or more accurately, the *cross sectional area* (since length is specified, as it is usually the case) must be related to the materials' mechanical strength and/or stiffness which therefore must be taken into account. This introduces a difficulty, namely that materials have to be compared in terms of more than one property. This difficulty is partially removed by the use of relations called *Merit Indices* (MI) or *Figures of Merit.* It can be shown [6, 7] that the weights of products or components made from different materials *and having the same performance,* scale with the expression:

$$\left[\frac{\tilde{n}}{E^{n}}\right] \quad \text{or} \quad \left[\frac{\tilde{n}}{\acute{o}_{y}^{n}}\right] \qquad [1]$$

where ρ is the density, E the elasticity (or Young) modulus, σ_y the yield strength and n is equal to 1 or _ or _ depending of the component's loading mode. Taking the example of beams with bending loads, where same performance means same deflection under the same load, we have n = _ [6, 7]. Table 1 summarizes the relevant properties and corresponding MI relative to the materials chosen for the beam. It must be pointed out that traditionally, MI are written as shown in the table, that is, the higher their numerical value, the lower the weight.

Material	E (MPa)	ρ (Mg/m^3)	$E^{1/2}$ / ρ	Weight ratio
Steel	210	7.8	1.9	1
Titanium	120	4.5	2.4	0.79
Aluminium	80	2.7	3.3	0.60
Magnesium	55	1.8	4.3	0.50
GFRP	40	199	3.3	0.58
CFRP	135	1.6	7.7	0.24

GFRP = glass fibres reinforced plastic; CFRP = carbon fibres reinforced plastic

Table I. Material Properties, MI and weight ratios of beams under the same flexural load, undergoing identical deflexion and built with different materials.

Figure 1 compares the weight ratios of the beams, calculated on the basis of the material's density only (Level 1) and of the relevant MI (Level 2). The influence of the the cross section shape on weight (Level 3) is discussed later.

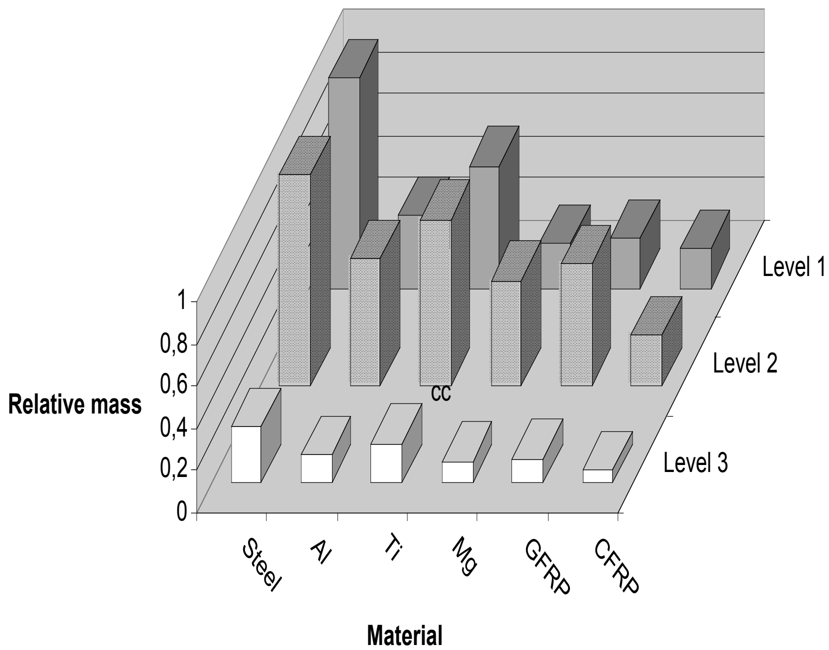


Figure I. Weight ratio of beams and tubes made of steel, aluminium, titanium and magnesium alloys, glass fibre reinforced plastic (GFRP) and carbon fibre reinforced plastic (CFRP). In Level 1, the weight calculations are based exclusively on material density; in Level 2 the same calculation are based on $E^{1/2}$/ _; on Level 3, besides the MI the weight calculations take cross section shape (moment of inertia) into account. Levels 1 and 2 refer to solid circular beams whilst 3 refer to tubes with constant thickness and variable outside diameter. All components display the same static performance, that is, they elastically bend by the same amount under the same load.

The differences are clear; for instance, selecting a GFRP the beam would be heavier than if a magnesium alloy were chosen, although the former has a lower density. The reason is found in the low modulus of elasticity of GFRP. Thus, final weight *for a given performance* is dictated by a combination of properties, not by density alone. Table II summarizes the MI employed in minimum weight design for different loading modes.

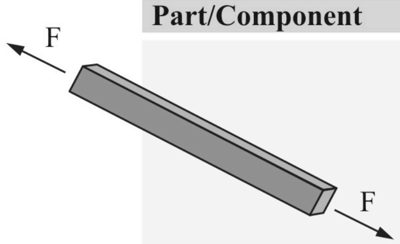
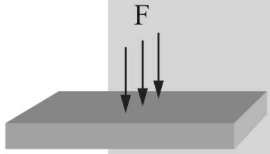
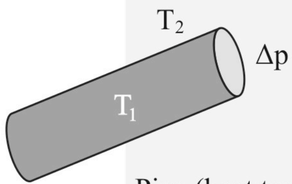
Part/Component	MI	Observations
 Tie bar (traction)	$\left[\frac{\sigma_y}{\rho}\right]$	If one changes the force (F) *maintaining the same material* (σ_y = const.), the cross section (A) must be changed accordingly, in order to compensate for the lower strength (σ = F/A) and maintain the same performance. In this loading mode, performance means the ability to sustain mechanical stress.
 Plate (bending)	$\left[\frac{E^{1/3}}{\rho}\right]$	Same observation. It must be recalled that in this particular case *performance* means "same deflection under the same force and for the same dimensions" - except of course for the cross section, in which thickness is the free dimension
 Pipe (heat transfer)	$\left[\sigma_y \cdot \lambda\right]$	Heat exchanger. Temperatures (T_i) and pressure difference (Δp) across the pipe wall. Maximizing the MI, the total heat exchange area and weight are minimized. (λ = thermal conductivity of the pipe material)

Table II. Loading modes of simple components and corresponding MI

In the Table, the MI's indicated are: [σ_y/ρ] in the first line and [$E^{1/3}/\rho$] in the second; the choice of one or of the other form depends on the structural design mode or criteria chosen by the engineer, that is:

- **Stiffness design mode**: once the envelope of forces (intensity, direction, periodicity) is known and the desired (or maximum) *elastic deflection* is assumed, the engineer proceeds to calculate the part or component cross section dimensions. This can be done using simple equations [12] or more advanced methods, such as *Finite Elements Structural Analysis* [13]. The material's property employed in structural design controlled by stiffness is the Young Modulus (E).

- **Plasticity design mode**: a stiffness designed product or component can be absolutely correct in terms of elasticity theory but: (i) for the specified elastic deflection the stress can be higher than the material's _$_y$, thus, instead of elastic the deflection will be permanent; (ii) there is no interest in specifying a given deflexion, but only to take maximum profit of the material's strength. In either case the important property is the yield strength (_$_y$). Table II shows a tie bar loaded in tension, a typical example in which structural design is yield controlled. Normally, stiffness design mode is employed when the component is subjected to bending loads, whilst the plasticity criterion is adopted when tensile or compressive loads are dominant.

- **Other design modes**: it must be remembered that loads are not always *mechanical forces,* but can be, say, thermal, as the third example of Table II shows. This is a pipe separating fluids of different temperatures (T_1, T_2) and subjected to a pressure difference (_p); hence, loads are both mechanical and thermal. Functional requirements are minimum weight and maximum heat transfer, and it can be shown [14] that the relevant MI is the product of thermal conductivity and yield strength.

In engineering design, shape also gets into the picture since the cross section profile determines to a great extent the load carrying capacity [6]. Experience shows that when working with low moduli materials it is customary to employ special cross sections; see for instance the intricacies of plastic chairs, adopted to increase stiffness. This has the effect of increasing a dimension called *second moment of inertia,* which can be understood as a load-carrying area [12]. This effect is demonstrated by Figure 1: Level 3 shows the relative weights of tubes made from steel, Al, Mg and Ti alloys, which exhibit the same performance of the solid beams. It can be seen that the weight has significantly decreased with respect to the solid component.

In conclusion, designing for low weight needs the concurrence of density with a property related to stiffness or to mechanical strength, more precisely the yield strength. These properties can be combined forming a MI with the form shown by equations (1). Thus, the larger MI, the lighter will be the product or component, and these quantities are inversely related. Loading conditions different from mechanical require a specific treatment to deduce the relevant MI.

II.2. Designing for heat resistance

At first sight, the property one should look for when selecting materials for heat resistance would be the melting temperature (T_m). However, a number of difficulties arise: (i) materials soften well before reaching melting point; (ii) in some cases they oxidize or degrade when approaching melting point; (iii) invariably, materials exhibiting very high T_m are difficult to process. Therefore, the relevant property when designing for heat resistance is the *maximum service temperature* (MST) which is normally well below T_m. Figure 2 shows MST values for selected polymers [15];

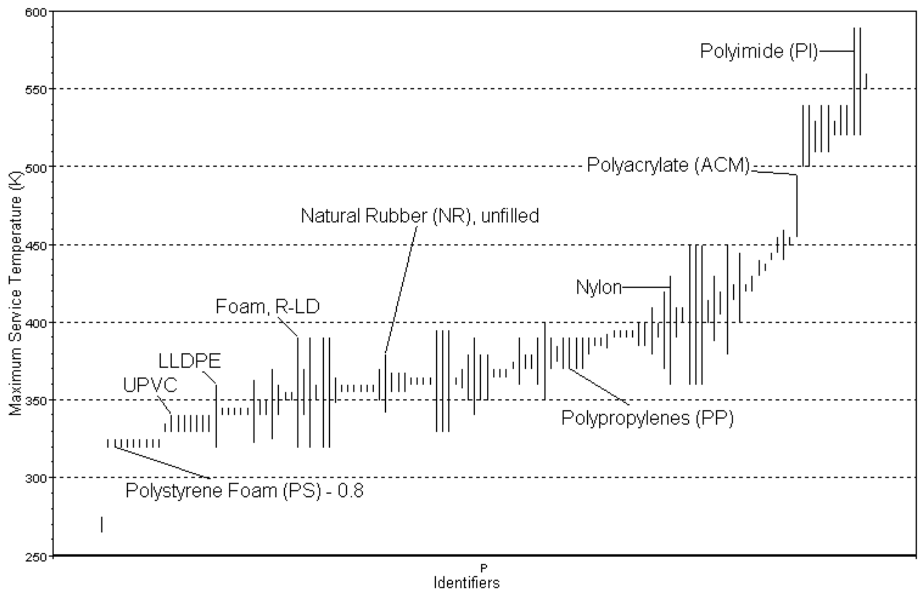


Figure II. Graph of the range of maximum operating temperatures for polymers.

Some working conditions in which thermal design needs to be taken in account are:

- Thermal insulation**:** an ice box is a product whose main requirement is to minimize the temperature rise after a specified time, for a given wall thickness. This is a typical case for minimization of short term heat flux;
- Thermal storage**:** system efficiency requires maximization of energy storage, for given temperature and time;
- Thermomechanical loading**:** thermal stresses are brought about by temperature changes. The relevant properties here are the *thermal expansion coefficient* (_) and the *thermal conductivity* (_). This type of

loading can provoke thermal distortion and affects thermal shock resistance, the latter being a form of failure caused by sudden temperature change.

Table III contains a selection of MI for thermal design. Properties from which they can be derived, are: thermal conductivity; thermal diffusivity (a); specific heat (C_P); thermal expansion coefficient, density and Young modulus. Figure 3 is a MPM designed to solve some thermal design problems [15].

Situation	Design requirement	Merit Index
Ice boxes, frozen food recyclable packages, saucers, isothermal containers for electronic equipment	Thermal Insulation (short term) Wall thickness specified, minimum heat flux at steady state	$\left[\frac{1}{ë}\right]$
Domestic refrigerators, furnace walls	Thermal insulation (long term) Maximize energy stored per unit material cost	$\left[\frac{a^{1/2}}{ë}\right]$
Storage heaters; items such as gloves, socks and caps; trays for warm food, thermal bags, thermal bottles.	Thermal storage Maximize energy storage for a given temperature and time	$\left[\frac{ë}{a^{1/2}}\right]$
Furnaces and domestic cookers components, medical equipment, measuring devices.	Minimum thermal distortion	$\left[\frac{ë}{á}\right]$
Medical equipment, re-usable containers for frozen food, plates and glasses.	Maximum thermal shock resistance	$\left[\frac{ó_f}{Eá}\right]$ (*)

(*) $\__f$ is failure strength.
Table III: Selected Merit Indexes for thermal design.

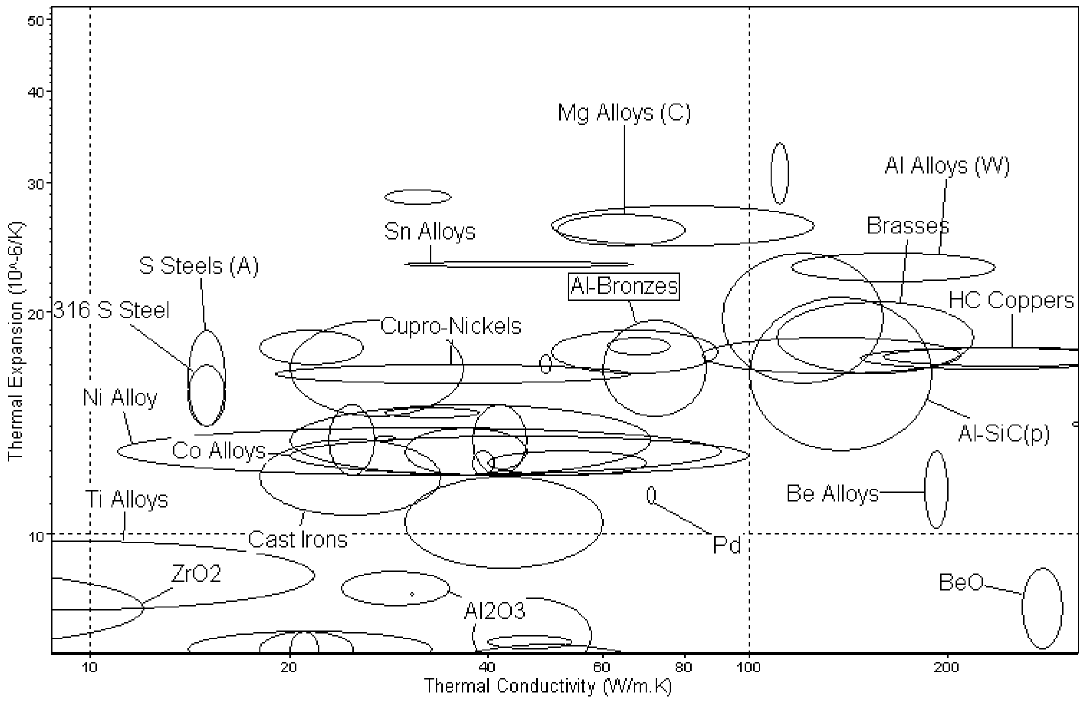


Figure 3. MPM for thermal design. Axes are thermal conductivity and coefficient of thermal expansion. Data can be employed to solve problems on short term heat insulation (maximize 1/_), and of minimum thermal distortion (maximize _/_).

The map is used in conjunction with Table III, which summarizes the relevant MI for thermal design. For instance, materials for short term thermal insulation (MI = 1/_) must be searched in a region located on the left side of the map, where thermal conductivity is very low. Therefore stainless steels, ZrO_2, nickel and cobalt alloys are good candidates; on the other hand, aluminium alloys, copper alloys and beryllium are not. When designing for minimum thermal distortion (MI = _/_), materials must be searched in the lower right hand side of the map. Thus, beryllium oxide and beryllium alloys (which, however, must be discarded by environmental and health reasons), SiC-reinforced aluminium and perhaps alumina, are suitable choices. For maximum thermal shock resistance (MI = $\_{f}$ / E_) a map can be constructed in which axis X = $\_{f}$ and axis Y = E _). This condition is typical of components such as Medical equipment, re-usable containers for frozen food, plates and glasses.

II.3. Designing for durability

Adverse environment and stresses of different nature can change the performance of a product or lead to its failure. Therefore after selecting the right material in terms of mechanical strength, cost, processability, etc., other factors related with operating conditions must be analyzed. Among a large array of possibilities, three situations will be here discussed: Corrosion resistance; Repeated stresses; Excessive wear or scratches to the product surface.

Current estimates put to 30% the cases in which corrosion is the primary cause for failure. However, MS based on corrosion resistance is a too specialized and complex issue to be analyzed here and the reader must be referred to other sources [16, 17]. Repeated stresses, on the other hand, can be correlated to a single mechanical property called *fatigue limit*. Whilst yield stress is a measure of mechanical resistance against *static* loads, the fatigue limit indicates which level of stress can be safely applied to the product for a very large number of cycles, say, 1×10^6 repeated applications. Most of the time, fatigue failure is typical of transport industry; for instance, 61% of all failures in aeronautical components are due to fatigue. However, even in some household products cyclic stresses can be a problem: cutleries, the handle of a paper-punch, the hinges of a mobile phone or of a notebook are only a few examples. Therefore, the fatigue limit must be taken into account. Normally, materials with high yield stress exhibit high fatigue limit.

Observation shows that mechanical damage, such as scratches, dents or unexpected wear, is a very common occurrence, even in normal use. Although the causes of excessive damage cannot be traced to a single property, in many cases it can be ascribed to insufficient hardness of the material. Figure 4 is a MPM which summarizes hardness data for metals and polymers [15]. It can be seen that the hardest polymer, which is polymide, is softer than any metal except lead and tin alloys. Iridium is the harder metal and it can be seen that some aluminium alloys are harder than ferritic stainless steels, thus can replace the latter as construction material for cutlery and furniture.

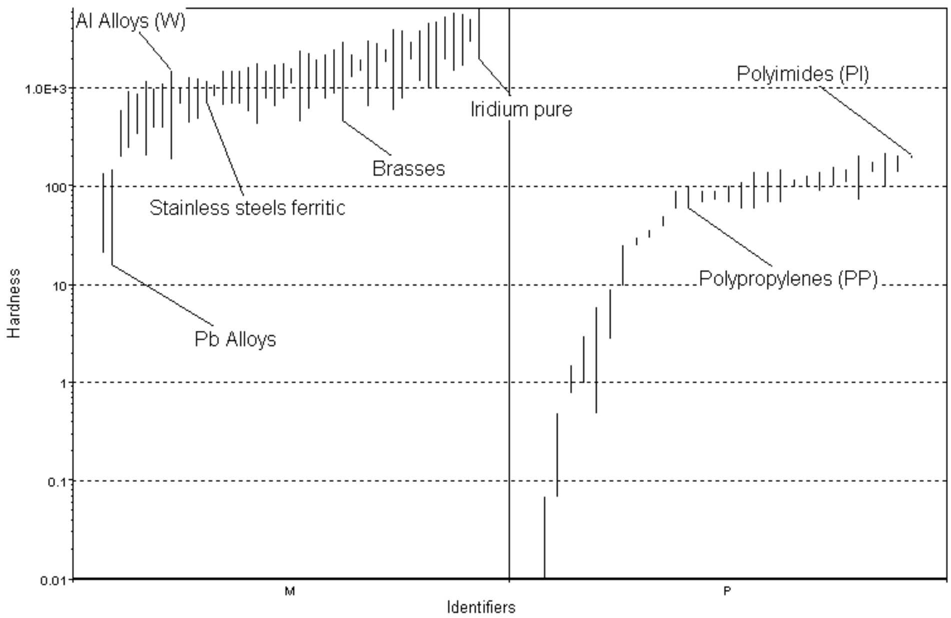


Figure 4. MPM showing hardness data for metals, metallic alloys and polymers.

III. Final considerations

Product design is a technical activity which thrives on creativity, artistic outlook and originality. However, to be successful, products must also be functional in the engineering sense, that is, they need to comply with performance requirements, with life expectancy and must resist to operational stresses and environmental action. One of the expertise which deals with this engineering aspects of product design is MS, and knowledge of materials and their properties can be a great asset for the product designer.

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