EFFECTIVE USE OF MATERIALS IN THE DESIGN PROCESS – MORE THAN A SELECTION PROBLEM.

S.N.B. Hodgson and J.F. Harper

ABSTRACT
This paper is concerned with addressing the common difficulties encountered by designers in optimising the form, function and fabrication of products to exploit and accommodate the characteristics of available materials. A structured approach is outlined, which provides an effective tool to assist the designer in identifying and responding to the materials considerations of the design in a balanced and holistic manner, based on the relationship of materials characteristics to principal design attributes.

Keywords; Materials, Design.

1 BACKGROUND

The efficient use of engineering materials is fundamental to product design. However with the growing range of engineering materials available to the designer currently estimated at over 100,000 [1] this is both an increasingly complex and critical part of the design process, and also provides growing opportunities for creative and innovative design. Each material offers distinctive characteristics and attributes which the designer can exploit as new design possibilities, whilst at the same time presenting an envelope of constraints, in terms of shape, size or geometry, processing capabilities and property characteristics within which the design must lie.

In design education, the effective use of materials is, in many cases, an afterthought or add-on to the core design methodologies commonly taught to students [2,3], which does not sit well with or integrate into them. Given the strong interaction between design, materials and manufacture such an approach is at best inadequate, and at worst can lead to critical design errors. In addition, overemphasis on simple post hoc materials selection stifles the opportunity for the creative use of materials within design.

2 USE OF MATERIALS IN DESIGN

This then begs the question how best to incorporate materials considerations into the design process. To address this it is important to consider the materials with regard to the three core elements of Form, Function and Fabrication. In fact effective design strategies require that materials considerations permeate each of these aspects. In addition, the materials used to embody the final design usually determine or influence the relationships between them. In reality, the choice of materials both influences and is influenced by each of these three aspects. Generally speaking, if the initial materials selection decisions are made on the basis of any one of these elements, then the balance between form, function and fabrication is adversely affected, as the other design elements are driven by the need to accommodate the capabilities of the materials chosen. Specific materials considerations thus need to be taken into account as an integral element throughout the design process.

In materials considerations as in all other aspects of design, it is inevitable that there will be a need to compromise some aspects of the design to achieve others. It is in determining the detail of the trade-offs between these objectives, whilst operating within the envelope defined by the critical design constraints, which truly test the skill of the designer. The materials aspects of the design are no different from any other in that the ability to achieve this is totally dependant on the ability of the designer to comprehensively and accurately define all the design requirements and develop a design solution that meets them.

2.1 Limitations of materials selection

Although, this represents a substantial oversimplification, in many approaches to design, the consideration of materials focuses almost exclusively on the process of materials selection. Over the last two decades, a number of materials selection software tools have been developed with the aim of assisting the designer, ranging from simple databases of properties and applications [4,5] through to complex engineering tools capable of dealing with multivariate considerations grounded in the basic physics and mechanics of materials [6]. If used appropriately all of these can be powerful and effective design aids. However, most designers experiences of their application to real multifaceted design problems are in fact a combination of confusion, frustration and disenchantment with the results achieved. In fact this is a classic case of "Garbage In Garbage Out" predicated by the design of the systems themselves in terms of the limited range and scope of input parameters available.

These limitations arise not from inadequacies from an engineering perspective, but rather stem from a failure both to engage with the designer, and with the full range of issues, which must necessarily provide the context and basis for the use of materials in product design. Perhaps most fundamentally, such systems fail to take account of the complex interactions which, in reality, occur between the various factors which comprise the design requirements, the identification, understanding and balancing of which are essentially the core skills of the designer as discussed above. These can be traced back to the (acknowledged) engineering bias of many such systems. It is of course much simpler to identify a material with an elastic modulus of X on a clearly defined numerical scale than it is to define a more subtle characteristic such as tactile response (although these may be inter-related), but it is the latter which ultimately is likely to be the dominant factor in the consumer purchasing decisions for a product which are the concern of the designer. Classic materials selection, typically neglects these critical second or third order materials characteristics, perhaps because in many cases the characteristics themselves and their relationship to the primary materials properties (such as strength, hardness, etc) have not been measured or formally defined, and focuses on a small subset of the full range of design requirements which are amenable to definition in terms of the primary materials properties, generating intrinsically unbalanced designs.

2.2 A holistic approach to use of materials

Within our University, we advocate an alternative approach to the consideration of materials in design. In this approach the design decisions relating to the materials are driven not by the availability of data, but by a rigorous, balanced and structured approach. In this approach the three elements of Form, Function and Fabrication are enhanced to consider a more detailed range of 10 materials related product attributes by which these elements are realised. These in turn ultimately determine both the cost and value of the product, which must ultimately match the need or market

Essentially, this process, illustrated schematically in figure 1, involves putting the materials at the heart of the design process, as the integrating element permeating all aspects of the design.

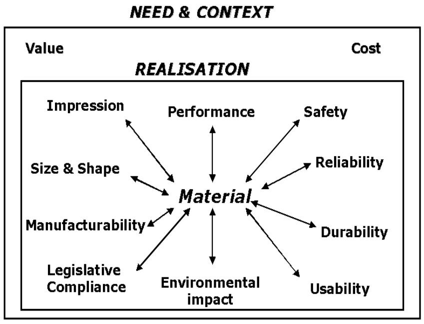

Figure 1: Relationship between materials & the elements of design.

This approach is much more compatible with the typical practise of most product designers, and is in effect a "materials specific" mirror of the widely advocated process of formulating a conventional product design specification [2].

Although engineering property requirements are an important consideration these are subservient to the user and producer definable attributes identified as meeting the design need(s).

2.2.1 Materials and Product Attributes

It is important to realise that all these attributes must be considered within the context of the market need for the product. This is itself determined by the factors which comprise the *"value"* of the product to consumers balanced by the product *"costs"* (as defined by the manufacturing costs and margins). Although not explained in detail here, these generic considerations must be defined, through consumer /market research and clearly identified price positioning as the context within which the other design attributes and the materials considerations are analysed

Although not every attribute will be of equal importance to every product, it is essential to ensure a balanced design that all these attributes are considered. This process in itself often reveals important materials considerations that must inform the design solution, which would otherwise go unrecognised. There will inevitably be some overlap between them but this can itself yield useful design information

As with all other elements of design, the first stage in this approach is to define the problem in terms of the deign needs and then develop one or more objective measures by which the relative performance of the design can be determined. Typically it is necessary to define both the acceptable operating envelope for this attribute, in terms of design constraints, as well as desired behaviours in terms of design objectives according to standard design conventions.

The next and key step in terms of materials considerations is to translate these characteristics into relevant materials characteristics that allow the desired behaviours to be embodied in the final design. These may be primary considerations such as a given strength or stiffness value, but frequently comprise more subtle combinations of two or more parameters, which are sometimes necessarily qualitative and subjective in nature. The range of attributes to be considered and some necessarily brief examples of their basic application follow. It is the authors' intention to explore each of these aspects and the related materials characteristics in depth in future publications.

Performance: Here, the factors that determine the extent to which the product fulfils its physical functions are identified and related to the characteristics of the materials used. Of all the attributes to be accounted for, these engineering aspects of the design are the most quantifiable and best defined. A considerable body of engineering literature exists, particularly with regard to the response of materials and structures to mechanical stress and thermal effects, [6] [7], with the best known being the so-called Ashby method [6] for determination of performance indices for materials selection and the related selection software system [8]. However, it is worth noting that such mathematically rigorous engineering approaches can often be dispensed with in practice when adopting the holistic approach to design proposed here unless mechanical performance dominates all the other design requirements. This simplification arises, since when the full range of design attributes are taken into account, then the necessity to compromise against other design factors typically outweighs the engineering performance considerations. At least initially it is normally sufficient to narrow down to the right "Ball Park" in terms of potential candidate materials. The key factor to be realised here is that *simply because these parameters are more easy to define this does impart them with any greater importance as attributes required of the design. There is little point in precisely defining the engineering attribute considerations if as is usually the case, the other equally important design attributes cannot be defined with equal precision*

Impression: Here we are defining the interaction between the product and the user through the physical senses of sight, touch, hearing and smell. The aim of the designer here is to maximise the pleasurability of the experience of the product., with a view to enhancing its desirability and thus marketability. Although routed in human psychology and physiology, materials considerations are all pervasive here as the substance through which the designers intentions are embodied and realised. The visual impression of the product is directly influenced by materials characteristics such as surface finish and texture, gloss, colour, reflectivity, transparency, texture. Acoustic impression includes both the level and quality of emitted sound from products, influencing user perceptions in both direct (this product is too noisy) and more subtle ways such as perceptions of build quality based on acoustic response such as the sound of a car door closing. Materials characteristics such as density, porosity and interconnectivity, damping coefficients/resilience and stiffness/elastic modulus all directly determine the acoustic behaviour allowing desired characteristics to be engineered through the appropriate use of materials. Even the smell of materials is known to influence consumer perceptions, for example the smell of upholstery in a new vehicle.

***Size and Shape*:** These attributes directly define the form of the product as well as its mass, which in turn make highly significant contributions to product costs and performance, and other aspects of impression. Materials considerations here include the direct contribution of material costs to product costs through the mass/volume of materials used, and the interaction between form and function as defined by the characteristics of the materials. For example we must account for the fact that the optimum shape of a part is different when designing materials with different physical properties such as rigidity or toughness. We can compensate for materials properties through modifications in shape, or vice versa. The key to success is to develop designs in which the characteristics of the materials used and the form of the part are mutually compatible and optimised.

Manufacturability: The characteristics of the materials chosen in the design, together with the design requirements in terms of shape, size and surface finish effectively define the choice of available manufacturing processes. However the fact that a process is *capable* of producing a given component is very different from its suitability for this and it is necessary to consider the relationships between the materials, manufacturing process and desired form to ensure these are mutually compatible. A number of sophisticated tools are becoming available to allow designers to predictively model the anticipated behaviour of a material within a manufacturing process; a typical example of this being Moldflow™ software for plastics injection moulding [9]. The different characteristics of materials can also impart many more subtle but important effects, which can substantially affect the economics of manufacture. For example the machining characteristics, the flow characteristics in a moulding, and the tendency to distortion after processing are just a few examples of factors that must be taken into account. The designer must ensure that the material and process route chosen are compatible with the cost requirements on the basis of the envisaged production volumes, capital/tooling costs, labour intensity/costs and production rates

Environmental Impact: The environmental responsibilities of the designer are an increasingly important consideration in the design process. Design for the whole product life cycle is above all else dependent on the materials used. These essentially define the energy requirements for materials production and processing into shape, and for usage of the product in service, the scarcity or renewability of the resources used, the biodegradability of the product, the recyclability of the product, the nature and extent of environmentally harmful by products, waste and emissions of manufacture (typically CO_2 or other gasses) and disposal (e.g. heavy metals in landfill etc). Unfortunately there remains scope for considerable improvement in the quality and comparability of the key metrics used in Life Cycle Analysis, but some good quality data sources are now becoming available for the designer. A notable example is the "IdeMat" programme [10] which allows objective comparisons of a wide range of materials on the basis of an eco-indicator score, and also provides input and output data to allow the material to be considered as a system.

Safety*:* It is a fundamental responsibility of the designer to predict and mitigate the potential of the product to cause harm both during manufacture and use. In many cases the materials used effectively define this. It is important to consider both acute and chronic effects. The latter are often easy to overlook. Acute effects such as physical trauma are typically functions of the deformation and fracture/failure behaviour of the materials used, whilst chronic effects are often defined by the chemical nature of the materials (toxicity) or physical property characteristics such as stiffness and density. The design of a tennis racket is a good example of this where high rigidity coupled with low mass, enhances performance but also exacerbate long term problems for the user such as tendonitis and stress fractures. Of course materials can also be used to actively enhance the safety of products, for example the use of compliant energy absorbing foams in vehicle design

Legislative compliance. Largely, this refers to compliance with the relevant legislation, directives and standards regarding product safety and environmental impact. Although these should in theory be included under the consideration of these attributes, separate consideration of the requirements for legislative compliance does provide "belt and braces", and ensures that the relevant design constraints are made explicit. With regard to materials considerations, specific legislation includes that regarding user safety (e.g. flammability and CE compliance) workplace safety (e.g. Control of Substances Hazardous to Health) and environmental protection Waste Environmental Electrical and Electronic Equipment, End of Life Vehicle Directive, as well as a huge range of other specific standards that must be complied with in particular product sectors.

Durability. Materials are the most important factor in determining product durability and life. The potential physical deterioration of the product due to materials related effects such as fatigue and wear must be taken into account, as must changes due to chemical changes caused by adverse interactions between the materials used with their local operating environment. Issues such as thermal, hydrolytic and chemical and light stability need to be considered. Corrosion control in metals is a particularly important consideration which it is worthwhile to highlight here also. In this and a number of other durability criteria, the behaviour is determined by the combination of materials used and the interactions between them. Frequently designers face a choice between achieving improvements in durability through changing materials or by protecting them in some way, perhaps by cooling, or coating. Informed decisions of this type require the impact across all relevant attributes (perhaps cost, impression, performance) to be considered.

Reliability and Maintainability. Although reliability is determined primarily at the component assembly level, materials issues can significantly impact factors such as service intervals, through properties such as dimensional stability. In addition, the ability to effect in service repairs by techniques such as welding, can often influence the long-term service life of products, with the materials used directly determining this. Secondary materials related considerations related to the product architecture are also of relevance here. For example, the effective exploitation of plastic materials to produce complex integrated mouldings and reduce assembly costs may also have adverse effects on the ability to maintain and repair the product cost effectively, requiring whole products or modules to be replaced rather than subcomponents. This might negate the initial benefits depending on the specific design need. Ultimately, an optimal solution can only be determined with reference to the balance between cost and value which forms the context for the design, and which determines the relative importance of this (maintainability) and the other design attributes

***Usability*:** Materials considerations are of importance in influencing the physical usability (& ergonomics) of a product rather than cognitive usability. Generally materials considerations are secondary factors here, for example, the materials used typically constrain the choice of available manufacturing processes and hence shapes which may in turn limit the opportunities to engineer ergonomically attractive products. However, materials can also directly influence product usability. This is particularly important in terms of the physical effort required to operate/use products. Appropriate use of materials in design can allow component weight and/or the force required to operate products to be reduced, for example by specifying materials combinations with intrinsically low coefficients of friction, such that products do not become "stiff" to use. This is of particular importance for inclusive design, for users whose physical capabilities may be such that the effects of inappropriate materials usage in design present real barriers to the use of products

2.3 Application of the attributes

Once the roles of the various design attributes have been defined, and the factors that determine them elucidated with regard to the materials (& other) considerations, the process of design can proceed by standard methods [2,3]. At this stage the design requirements (and/or elements of the PDS) can be ranked, weighted and prioritised, through the use of requirements trees or similar structured approaches.

It is often helpful to structure the design requirements and product design specification for the product with the requirements grouped under the headings described above for consistency and to ensure that all of the key materials considerations are properly accounted for, expanding and combining these to encompass any other important issues which may not be materials related. This might include aspects such as documentation, user training etc.

It is recommended that the design attributes be considered initially at the whole product level, before moving to and repeating the process at the component level necessary to define materials requirements. As a final check we recommend that in the final stages of design, the whole-product and component level design attributes are cross-checked to ensure that the desired characteristics have been incorporated.

3 CONCLUSIONS

The synergistic combination of materials and design is the key to the development of efficient and desirable products. Materials are more than just that from which the design is embodied, but rather can be considered as the integrating element of form, function and fabrication. Many deficiencies in product design can be traced back to post hoc selection of materials, which fails to adequately take account of this. The materials considerations need to be treated as an integral and permeating element of the design process, both informed by and informing the design decisions. The key step in facilitating this is in identifying and subsequently analysing the full range of materials related design attributes with respect to the design need in the context of cost and value factors as drivers for the design. A practical approach to the effective use of materials in design has been outlined in which the full range of materials related product attributes are evaluated in a systematic process, which ensures that a balanced perspective is taken to the materials considerations, and that the value ascribed to materials characteristics is consistent with their importance to the design rather than biased by the availability and reliability of the materials property data itself. Such an approach is of considerable value as a design tool, which can be used through all stages of the design process, including as an aid to creativity at the conceptual design phase.

REFERENCES

[1] Kutz., M. (ed), "Handbook of materials selection" Wiley, 2002.

[2] Pugh, S. "Total Design, Integrated methods for successful product engineering", Addison Wesley (1991)

[3] Pahl, G, Beitz, W. "Engineering design; A systematic approach", Springer Verlag, (1996)

[4] Anon.. 'A to Z' of materials launched online" MATERIALS WORLD 9 (9): SEP 2001

[5]. Automation Creations Inc "Matweb-Materials property database, http://www.matweb.com/,

[6]. Ashby M.F, Cebon D, "Materials Selection In Mechanical Design" Journal De Physique IV, 3 (C7): 1-9 [1] (1993)

[7] Ashby M.F, "Materials Selection in Mechanical design, 2nd ed, Butterworth Heinemann (2001)
[8] Cambridge Engineering Selector Software v4, Granta Design Ltd, Cambridge (2003)
[9] Moldflow Part Adviser Software, Moldflow Corporation, Wayland, US (2003)
[10] IdeMat 2002 Software, Delft University of Technology, Fac. of Design, Delft, Nl (2002)

Contact Information:
Dr Simon Hodgson,
Loughborough University,
Institute of Polymer Technology & Materials Engineering,
Loughborough,
Leicestershire, UK.
Tel. + 44 (0)1509 223152
Email: S.N.B.Hodgson@lboro.ac.uk