Materials and Design 56 (2014) 44–49

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Proposal for a multi-material design procedure

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ARTICLE INFO

Article history:
Received 21 May 2013
Accepted 4 November 2013
Available online 13 November 2013

Keywords:
Multi-materials
Design
Materials selection
Architectured materials

ABSTRACT

This paper describes a proposal for a multi-material design procedure. First, the context of the study and the requirements of the multi-material must be clearly defined in order to specify the parameters that the designer must select or optimise in order to produce the design: the components and their volume fraction, the architecture and morphology at different scales, etc. The general design procedure proposed here starts with the reasons why the designer has turned to multi-materials, from which a multi-material concept with fixed parameters can be defined. In this first stage the design problem can be made less complex by reducing the number of unknown parameters and guiding the designer towards the appropriate selection or optimisation tools: (i) subdivision of requirements, guided by applying statistical analysis tools to the materials database to search for appropriate multi-material components, (ii) tools to filter the materials database and search for multi-material components and their volume fraction, (iii) optimisation tools to search for the appropriate architecture when components are known or to search for architecture and components simultaneously. The paper demonstrates how these tools can be applied to different design concepts.

1. Introduction

To optimise the cost and technical characteristics of products, designers nowadays tend to integrate more and more functions into a single part, with the result that more and more requirements are placed on the part material. This is the case for materials used in aeronautics, for instance, which have to be not only light but also stiff or strong; by using multi-layer structures and especially sandwich solutions, these objectives can be achieved [1,2]. In the clothing industry, there is the example of technical materials which as well as being comfortable and providing protection can also incorporate antibacterial functions, thermoregulation, etc. [3]. Multifunctional materials have also been developed to protect against electromagnetic radiation [4], and to provide acoustic or thermal insulation [5,6].

Different design strategies are possible depending on the situation: the designer may develop a new material, he may adapt an existing material, or he may define a combination of materials, in other words design a multi-material.

In accordance with the definitions proposed by Ashby, Bréchet, or Kromm [7–9] a multi-material or an architectured material is considered to be the association of one or several materials disposed according to a predefined architecture such that a representative elementary volume has at least one dimension that is very small compared with the dimensions of the part that it composes.

The parameters that the designer must define in the design of a multi-material are:

- Components, these are usually materials, but they may also be semi-products, this is the case, for example, for multilayer structures or stratified composites.
- Volume fractions of the components.
- Architecture and morphology of the components, i.e. their spatial disposition.
- Coupling modes between the components, especially the nature of the interfaces and their behaviour.

The manufacturing process of the multi-material also has an influence on its characteristics.

The variety of means at the designer's disposal for solving a design problem results in considerably more extensive requirements and functions for a multi-material than for monolithic materials. Multi-materials are therefore used more and more frequently for industrial products but usually derive from empirical design methods and are rarely the result of a systematic rational method. This means that designers do not derive all the possible benefits that could be expected from the multi-materials.

In order to build a multi-material design method, several concrete cases are studied. These studies showed that this design process could be divided into different categories, each corresponding

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http://dx.doi.org/10.1016/j.matdes.2013.11.004

to the search for one element in the multi-material while the other elements remained fixed, for example searching for components when the architecture and the interfaces are defined. This reduces design complexity.

In order to build up a rational multi-material design process it is relevant to give the reasons why the designer has decided to use this type of material. Moreover, if the designer agrees to limit somewhat the degree of creativity inherent in any design process, then the problem is considerably simplified. The method proposed here is based on analysis of the reasons why no monolithic material solution exists, which then allows the designer to focus on a limited area, either searching for the multi-material components, or defining its architecture, or the coupling modes between components. As a result, selection tools, and especially materials selection tools, can be applied to multi-material design.

The aim of this paper is to propose a *structured* method for multi-material design. Different tools derived from various domains like design, materials selection, or optimisation, are presented as illustrations.

2. Selection tools or optimisation tools

In the domain of choice of materials and processes, although the space for the coupling modes (materials, processes) is vast, it is nevertheless countable, in other words, a search for a monolithic material and a production process can be carried out using selection methods in a correctly structured space. However, if a continuous variable is also a parameter defining the candidate solution, then selection methods are no longer sufficient and optimisation methods must be used to explore the candidate space. When designing multi-materials, if certain qualities can be fixed and the multi-material candidates are countable, then a selection method is appropriate, as is the case, for example, when searching for components when all other characteristics are fixed. If, on the other hand, the multi-materials are defined by continuous variables then a discrete selection procedure is replaced by a design continuum procedure; in this instance, optimisation tools must be used.

Before defining the search procedure for a multi-material solution, the reasons why such a solution is necessary will be examinated. This analysis will be integrated into the proposed design method.

3. Why a multi-material?

The aim of reducing costs and improving the performance of technical products drives the designer to incorporate more and more functions into the material, but also to require higher performance characteristics of the materials. As a result, searching for a solution based on a monolithic material is often unsuccessful, and it becomes necessary to design a multi-material to find new solutions. The reasons that guide a designer to multi-materials are varied, so a few examples will be examined to take these reasons into account in a design method:

- Improving the performances of a part: it often happens that the users and/or designers of a product increase the level of their requirements and want to improve performance, where performance is understood to be a level of obligation, such as increased strength or stiffness of a part, increased service life, reduced mass, decreased overall dimensions, etc. This increase in the level of obligations may render the search for a monolithic material unsuccessful as the screening parameters become more stringent.
- Incompatibility with the requirements: a search for monolithic materials may still be unsuccessful even when the level of constraint required is reduced considerably. This happens when constraints are incompatible: for example, the search may require a material that has both good thermal conductivity and high electrical resistivity.
- Integrating new functions into the material: more and more often the trend is for designers to integrate new functions into a material. One remarkable example is the car windscreen, whose primary function is to protect the driver from the external environment; more functions have gradually been added and the windscreen is now required to contribute to the overall stiffness of the chassis, to protect the interior from the sun's rays, to provide heat protection, to be self-defrosting, to provide aerial wave reception and soon it will become a screen on which to display information... No monolithic material can fulfil such a wide set of requirements.
- Reducing manufacturing or operating costs: this reduction may be linked with the cost of the material (see the historic example of talc in polymers). A decrease in operating costs very often corresponds to a decrease in mass, which in the area of transport is correlated with an increased payload or a reduced energy consumption.
- Facilitating manufacturing: the complex geometries that can be obtained when using composite materials often means a reduction in the number of parts needed to produce a unit; this is the case, for example, with the rear tail unit of certain aircraft which is made of one piece, whereas with metal design, it would have to be assembled from a large number of parts.
- Not overdimensioning the part: a part is not overdimensioned if the functional requirements are fulfilled exactly. The number of free design variables is also the number of functional requirements verified without overdimensioning. If this number of free design variables is increased when designing multi-materials in accordance with material selection then overdimensioning of the parts can be reduced.

This non-exhaustive list of reasons explains why a search for a monolithic material may prove unsuccessful. This preliminary analysis will be used in the search for the multi-material solution.

4. Designing a multi-material: Strategy for a "toolbox"

Just as in the search for a monolithic material, the proposed multi-material design method starts by setting out the material requirements, based on the functional requirements of the part. Next, an expert questionnaire has to be created. This questionnaire is constructed around the question "Why a multi-material?". Note that this question also implies an understanding of why a monolithic material cannot be the solution to the problem.

Usually, an expert questionnaire is used to explore a solution space. For example, this type of questionnaire is used to select materials for electrical connectors [10] or for selecting assembly [11] or operation processes [12,13]. The main aim is to collect information extracted from standard practice that can guide the designer through the design method. The expert questionnaire depends on the application domain for which the multi-material is intended and on the experience of the designer. The main questions are:

- Which materials are closest to the target objectives?
- What constraints prevent a monolithic material being selected?
- Are the requirements in the specifications compatible?
- Is there an architecture that is already used in this type of application?