Materials & Design 83 (2015) 704–712

Contents lists available at ScienceDirect

Materials & Design

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

A material selection approach to evaluate material substitution for minimizing the life cycle environmental impact of vehicles

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ARTICLE INFO

Article history:
Received 31 March 2015
Revised 30 May 2015
Accepted 8 June 2015
Available online 19 June 2015

Keywords:
Lightweight design
Material selection
Life cycle assessment
Sandwich structures
Self-reinforced composites

ABSTRACT

Weight reduction is commonly adopted in vehicle design as a means for energy and emissions savings. However, selection of lightweight materials is often focused on performance characteristics, which may lead to sub optimizations of life cycle environmental impact. Therefore systematic material selection processes are needed that integrate weight optimization and environmental life cycle assessment. This paper presents such an approach and its application to design of an automotive component. Materials from the metal, hybrid and polymer families were assessed, along with a novel self-reinforced composite material that is a potential lightweight alternative to non-recyclable composites. It was shown that materials offering the highest weight saving potential offer limited life cycle environmental benefit due to energy demanding manufacturing. Selection of the preferable alternative is not a straightforward process since results may be sensitive to critical but uncertain aspects of the life cycle. Such aspects need to be evaluated to determine the actual benefits of lightweight design and to base material selection on more informed choices.

1. Introduction

The transport sector accounts for about one third of total energy demand in Europe and is among the major contributors of greenhouse gas emissions [1]. Road vehicles have a considerable share in this. To meet increased regulations and customer requirements for reduced environmental impact, the automotive industry seeks solutions to improve the performance of their fleet especially during the dominant operation stage. Weight reduction is commonly adopted in vehicle design, resulting in both energy and emissions savings [2,3]. Weight savings can be realized through material substitution to lightweight materials, such as lighter metals, polymers and composites [4,5], through use of materials in a more weight efficient manner, for instance as a sandwich structure [6], or through a combination of the two. Lightweight design does, however, have drawbacks. Compared to steel, composite materials such as carbon fiber reinforced polymers (CFRPs) are costly and have higher energy demand during manufacturing [5]. Recycling of composites and sandwich structures is also costly and complicated; since composites consist of two different materials (matrix and reinforcement) and traditional sandwich structures often consist of three (face sheet-, core material and adhesive), separation of the materials is difficult. A relatively new class of composite materials, self-reinforced polymers (SrPs), also called single-polymer or all-polymer, could combine weight savings with high recyclability at end-of-life (EOL), since fibers and matrix are based on the same recyclable polymer [7,8]. They also exhibit good mechanical properties [9,10] and may hence be attractive for automotive applications. To assess whether there are any significant unexpected environmental trade-offs over the life cycle, these novel materials need to be assessed using a life cycle perspective. Such an assessment should consider physical, mechanical, and environmental characteristics in an integrated manner [11] and be adopted in standard material selection and vehicle design processes. Such assessments are rarely applied in practice, as vehicle designers primarily consider performance and acquisition cost of the material [12] while environmental performance is rarely prioritised [13,14]. If performed, environmental assessments are usually done for finalized products, not as an integrated part of the design process [13,15]. For the automotive industry to meet the challenge of reducing the climate and other environmental impacts, a shift in the material selection paradigm is needed. Eco-design guidelines, e.g. ISO TR 14062 [22], suggest that environmental assessment should be performed in parallel to the traditional product design process and before any final design

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http://dx.doi.org/10.1016/j.matdes.2015.06.079
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decision is made. Hence, comprehensive frameworks are needed which ensure that both functional and environmental vehicle performance requirements are considered and balanced. Although rarely applied in practice, several such integrated models for evaluating and selecting materials can be found in literature [3,5,16–20]. Simoes et al. [3] and Witik et al. [5] suggest a thorough environmental and cost analysis. However, design parameters and requirements are not presented as part of a comprehensive material selection model, limiting those studies to an environmental and cost assessment of finished products. Only a few complete frameworks for material selection in a design context based on structural optimization and life cycle environmental assessment techniques have been published [16,18,20]. Some of these are prescriptive, for instance concerning the use of preselected environmental indicators or decision making functions. While this may simplify application, there is also a risk that it prevents integration in a company's established material selection process.

1.1. Aim and scope of the paper

An integrated material selection approach is presented in which structural weight minimization is combined with environmental life cycle assessment (LCA), with the aim to allow for systematic evaluation of material alternatives before any final design decision, and to reduce the risk for sub-optimizations and shift of environmental burdens along the different life cycle stages of the vehicle. It builds on previous frameworks and expands their scope especially concerning environmental performance of the materials. Efforts were made to capture critical aspects in vehicle design. The approach was tested on a vehicle design case study. SrP composites were compared to commonly used materials for a particular vehicle component, in order to show how materials for vehicle design can be systematically assessed, but also to provide specific results regarding the environmental performance of SrP composites.

2. Life cycle based material selection

The integrated material selection approach was aligned to traditional material selection frameworks that consider material properties and structural weight optimization to derive feasible and weight efficient design alternatives [21]. It adds evaluation of life cycle environmental impact of all feasible material alternatives at an early stage. It consists of five major steps; Definition of design target, Selection of material families and candidate materials, Weight minimization, Life cycle modelling and assessment, and Results analysis and material selection (Fig. 1). Selection of weight minimization models, environmental analysis tools and impact indicators are to be decided by the users. Possible ways to analyze and interpret the results are suggested. Although cost is an important parameter in material selection today, it is not considered in this study.

2.1. Definition of design target; setting requirements and constraints

Design targets are defined by a number of functional (fundamental properties) and non-functional requirements according to the intended application. These requirements need to be fulfilled in a limited design space. A functional requirement of a car roof for instance, is to protect passengers from outdoor conditions and from accidents. In this material selection approach, low environmental impact is also considered a functional requirement of the design target as suggested by Deutz et al. [23], in order to "extend the definition of functional requirement" from considering only the performance of the product to its life cycle performance. Additionally, properties related to the intended application (vehicle) may also have an influence and restrict the design target. The type of vehicle and operating conditions (including total life time and environmental conditions), legislation as well as corporate requirements are some examples related to the intended application.

2.2. Selection of material families and candidate materials

Engineering materials can be classified into six families: metals, ceramics, glasses, polymers, elastomers and hybrids [21]. The functions and requirements defined by the design target constrain the selection of certain material families [24]. A front window of a vehicle for instance should be transparent which obviously excludes the use of metals. From the remaining families, a more specific list of properties and constraints (such as application temperature, specific strength or stiffness, manufacturing constraints, and regulation requirements) will lead to only a few representative alternatives or material candidates that fulfil the design target [13,18,24]. Those materials represent feasible design solutions for the design target and will be used in the consecutive stages of weight minimization and life cycle assessment applied in this approach.

2.3. Weight minimization

Weight minimization is applied to all material candidates in order to derive the lowest optimal mass for the design target. For the weight minimization, constraints such as available space for the part or maximum allowed deformation are defined based on the requirements of the design target. The general constraint optimization problem is formulated as:

$$\text{minimize} \quad f_0(x_{(1:i)}) \tag{1}$$

$$\text{subject to} \quad f_k(x_{(1:i)}) \leqslant b_k, \quad k = 1 \ldots n \tag{2}$$
$$\underline{x_i} \leqslant x_i \leqslant \overline{x_i}, \quad i = 1 \ldots 5$$

f_0 is the weight function which is a function of the design variables x_i. f_k is the constraint function while b_k represent the constraint values. $\underline{x}$ and $\bar{x}$ define the lower and upper bounds for the design variables x_i. These bounds could be for instance the allowed wall thickness of a structure.

2.4. Life cycle models and assessment

Life cycle models of each candidate material are created and assessed according to [25]. The functional unit (reference measure of the assessment) [26] defines the function and operational life of the design target and remains constant for all design alternatives in order to provide comparable results. Environmental inventory data (inflows of energy and materials and outflows of emissions and waste) are collected for all stages and processes involved, either from generic material databases e.g. [27,28], suppliers, or manufacturing sites. The potential environmental impact of the design alternatives can be estimated with life cycle impact assessment (LCIA) methods [29] that quantify the impact of resource use and emissions [26]. The most appropriate LCIA method is determined by the availability of data, quality of the model, as well as the aspects that the designer wants to consider. Different software tools are available to facilitate data collection and calculation procedures.