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Optimization and lifecycle engineering for design and manufacture of recycled aluminium parts

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ABSTRACT

Aluminium alloys components are numerous in aeronautic and automobile structures. Despite having interesting mechanical properties for lightweight solutions, the extraction of virgin aluminium still has negative impacts on the environment. A solution is to use an increased rate of recycled aluminium in structural parts. This requires a global optimization of the part design and manufacture. The proposed work details the advanced optimization techniques used for product and process design integrating environmental concerns. The methodology is implemented and tested on an industrial case that results in a recycling rate of 75% in high-end structural component based on wrought aluminium alloys.

1. Introduction

Optimized lightweight manufacturing of parts is crucial for automotive and aeronautical industries in order to stay competitive, and reduce costs and fuel consumption. Hence, aluminium becomes an unquestionable material candidate regarding these challenges. Nevertheless, using only virgin aluminium is not satisfactory since its extraction requires high use of energy, and its manufacturing has high environmental impacts. For these reasons, the use of recycled aluminium alloys is recommended since their properties meet the expected technical and environmental requirements [1]. This requires complete reengineering of the classical lifecycle of aluminium-based products and several interdependent disciplines need all to be taken into account for a global product/process optimization [2]. Towards this end, the paper proposes a method for sustainability assessment integration into product lifecycle engineering and a platform for lifecycle simulation integrating environmental concerns. The platform may be used as a decision support system in early product design phase by simulating the lifecycle of a product (from material selection to production and recycling phases) and calculating its impact on the environment.

1.1. Sustainable engineering, integrated lifecycle and design optimization

Design, as defined in [3] is a complex and multifaceted phenomenon involving a tight collaboration between multi-domain product designers, a multitude of activities and procedures, tools and knowledge, as well as a variety of contexts.

Collaboration between multi-domain product designers implies that different points of view must be taken into account to achieve the best compromise in product development [4]. A point of view is the vision and knowledge of an expert involved in a design team [5]. An expert may be specialist of a particular lifecycle stage (e.g. manufacturing), a domain (e.g. mechanical engineer) or cross-domain (who brings expertise not linked to a life stage or a domain, but to a specific point of view on the whole lifecycle of a product, as for example the quality engineer or the environmental expert).

The environmental experts often have difficulties to share environmental information with other design experts [6,7]. This could be due to the nature of the results (e.g. environmental impacts) which are difficult to link with other design parameters (material specifications, geometric models, etc.). It can also be due to the absence of a standard exchange format that encompasses environmental parameters, like STEP (Standard for the Exchange of Product model data) that allows information exchange between various experts tools [8]. This results in the lack of interoperability between the systems used in design and those used by the environmental experts.

To go beyond these issues, Rio [9] proposed a model-driven architecture based interoperability method to improve exchange of information between eco-design and other design activities. Some software vendors worked on the integration of sustainability in traditional design tools like CAD systems (Solidworks from Dassault Systèmes) or material selection tools (CES selector from Granta Design). Russo and Rizzi [10] suggested another integrated eco-design method, including shape, material and production

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assessment integrating Life Cycle Assessment (LCA) with CAD and Finite Element Analysis. But those modules focus on a specific design stage and do not consider environmental impacts on the whole lifecycle. Other researchers, like Dufrene et al. [11] proposed an integrated eco-design methodology that improves both environmental impacts and technical characteristics.

One of the major difficulties the environmental experts have to cope with is the lack of information especially when they try to perform LCA [12,13]. LCA is time and resource consuming and requires a huge amount of heterogeneous data from all over the extended enterprise. Stark and Pförtner [14] proposed an ontological approach to assess sustainability based on information from IT systems and calculation rules. Some of this information could be extracted from the digital mock-up. This requires integration between CAD, Product Lifecycle Management and LCA, but to make a clear and useful analysis of environmental impacts, this information must be specialized and accurate [15].

1.2. Objective

A design methodology that integrates whole lifecycle environmental impact assessment into a product design optimization loop is not yet realized. In order to include the entire lifecycle environmental impact, the assessment of the optimized design should take into consideration the extraction, manufacturing, distribution, use and end of life. This leads to a methodology that integrates environmental concerns into a closed loop design optimization. The optimization includes material choice (based on recycled aluminium compositions), topology optimization for this particular material, optimization of processes and tolerances, and simplified environmental assessment. The objective is to propose new materials, processes and parts design that fulfil high level requirements and decrease total environmental impacts.

2. Proposal: the SuPLight closed loop design methodology

The methodology is developed in the European project SuPLight (Sustainable and efficient Production of Light weight solutions). SuPLight is a multidisciplinary research project, combining physics at the atomic scale level, metallurgy, continuum mechanics, structural mechanics, optimization algorithms, tolerance analysis, and manufacturing and lifecycle assessment. SuPLight proposes to reduce weight in structural parts and improve the holistic eco-design of aluminium wrought alloys and to build novel sustainable industry models with a holistic lifecycle approach.

This methodology is based on an optimization loop on material, part topology, processes and parts tolerances and environmental assessment (Fig. 1). It is supported by an integrated optimization platform that supports automatic data exchange between the different tools.

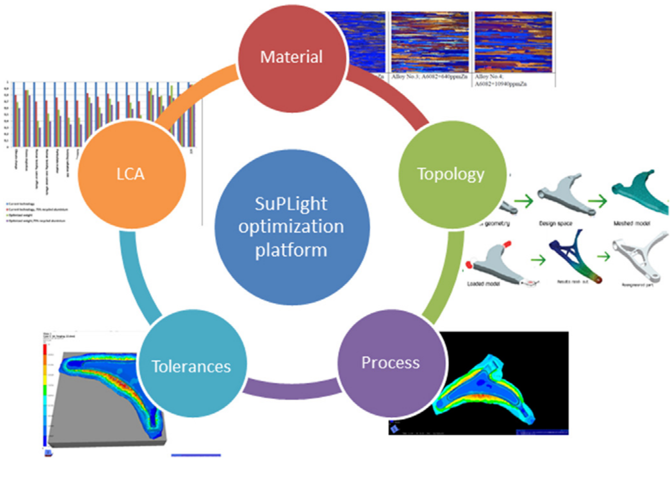

Fig. 1. SuPLight overall methodology.

The material phase determines the material and mechanical properties of the alloys which are later used by the design optimization and process phases to calculate the behaviour of the alloy parts.

The design optimization performs an analysis in order to find alternative topologies for the part that fulfil the stiffness, weight criteria, eigenvalues and centre of gravity requirements. The output of this phase includes the geometry definition used as an input to the process optimization phase.

The process optimization phase assesses the forging process for the part defined by the design optimization. The output of this phase includes the geometric definition for the tolerance phase input.

The tolerance optimization uses a meta-model for tolerance analysis and geometric variation simulation to provide rapid results based on a more extensive computation module.

The environmental assessment computes environmental impacts based on the characteristics of the product. The simplified lifecycle assessment of the part (in its context of usage) is based on the inputs from the other phases.

2.1. Material

Based on the chemical composition of the target alloy and its processing path the analysis returns the set of relevant material properties. The composition of the alloy can be specified by its unique ID based on the predefined set of alloys or by element composition. The processing path can be either (1) die cast and forging, (2) continuous casting and forging, or (3) continuous casting, extrusion and forging.

The material properties are calculated using two different scenarios: basic usage and advanced usage. In the case of basic usage, the material properties are evaluated by means of meta-models based on the experimental data. On the other hand the advanced operations allow the evaluation of mechanical properties of the alloy by metallurgical precipitation hardening model. In the initial stage the model is based on classical Kampmann–Wagner model [16]. Due to the known limitations of this model with respect to thermodynamics, the additional model SFFK was implemented [17]. The latter model gives the possibility to overcome limitations of Kampmann–Wagner model approach by allowing modelling of multicomponent and even multiphase systems. The developed framework allows wide range of adaptations of the model and introductions of additional components. As a first validation, successful initial testing was performed using the thermodynamic data from literature and other sources.

2.2. Topology optimization

In structural optimization, the use of different sets of data representing a mathematical model describes the behaviour of a structure. Different control parameters are tuned by a set of design variables to find a situation in which the structure meets a given property. Shape optimization consists of optimizing the structure by changing the shape. Shape optimization has an interdisciplinary character, meaning it can be used on a wide range of problems. This kind of problems involves mathematical disciplines as partial differential equations, approximations of these and theory of nonlinear mathematical programming. This process is an automated and integrated task in the proposed framework.

2.3. Process/manufacture engineering

The use of specialized codes to predict material flow during forging has been developed together with of the rapid growing of computer-aided engineering, e.g. FORGE NxT. In contrast to structural design, the codes for handling forging are typical set up to manage large strains and deformations. Combining the predictive capabilities in such codes with an optimization engine gives an advantage for designing sustainable and optimal forging

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