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Research paper

A methodology for microstructure-based structural optimization of cast and injection moulded parts using knowledge-based design automation

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ABSTRACT

The local material behaviour of cast metal and injection moulded parts is highly related to the geometrical design of the part as well as to a large number of process parameters. In order to use structural optimization methods to find the geometry that gives the best possible performance, both the geometry and the effect of the production process on the local material behaviour thus has to be considered.

In this work, a multidisciplinary methodology to consider local microstructure-based material behaviour in optimizations of the design of engineering structures is presented. By adopting a knowledge-based industrial product realisation perspective combined with a previously presented simulation strategy for microstructure-based material behaviour in Finite Element Analyses (FEA), the methodology integrates Computer Aided Design (CAD), casting and injection moulding simulations, FEA, design automation and a multi-objective optimization scheme into a novel structural optimization method for cast metal and injection moulded polymeric parts. The different concepts and modules in the methodology are described, their implementation into a prototype software is outlined, and the application and relevance of the methodology is discussed.

1. Introduction

As the demands for low weight, reduced emissions and reduced environmental impact increases in areas as e.g. transportation and outdoor power products as chainsaws, the request for optimization of engineering structures increases accordingly. This drives the importance of designers to increase the load-bearing efficiency of parts, and increases the request for Computer Aided Engineering (CAE) tools and methods, as shape and topology optimisation, to identify geometries that fulfils the specified objectives. However, in order to be truly optimal from a company and customer perspective, the part also need to simultaneously fulfil a multiple of other objectives, as high manufacturability and robustness, legislation demands, and ergonomic aspects as low levels of noise and vibrations. To successfully meet all these objectives in a short development time, a close interaction and collaboration between many different areas of the industrial product realisation process is required [1].

Many materials exhibit an interdependence between manufacturing and material behaviour. Casting is a manufacturing process able to generate near net shape components, while producing complex geometries in small as well as large series in a cost efficient manner. This design freedom is further enhanced by new technologies as e.g. 3D printing of moulds [2], making casting a modern technology highly suitable for creating parts with complex geometries and high load-bearing efficiency. During the solidification of cast metals, local variations in e.g. geometry and solidification conditions causes local variations in microstructure, leading to local variations in material behaviour throughout the geometry. These variations have been found to being able to alter the distribution of stresses and strains in castings when the casting is subjected to load [3]. Geometrical changes alter this heterogeneous distribution of material behaviour, thus causing an interdependent relationship between geometry and material behaviour that needs to be considered in structural analyses methods for castings. To address this topic, a simulation strategy denoted *the closed chain of simulations for cast components* has previously been presented by one of the current authors [4]. The strategy uses casting process simulations to generate microstructure-based mechanical material behaviour,

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which is incorporated into Finite Element Analyses (FEA) of the casting.

In injection moulded polymeric parts, especially made in glass-fibre filled materials with highly anisotropic material properties dependent on the glass-fibre orientation [5], manufacturing parameters as ingate position etc. highly influences the distribution of variations in local material properties in a part as well as the position of local reductions in mechanical properties by e.g. weld lines [6].

It is thus of utmost importance that these effects of the manufacturing process on the local material performance is considered in geometrical optimization methods, or incorrect predictions will be made and incorrect conclusions will be drawn regarding the behaviour and performance of the part in operation.

Previous structural optimisation methods for cast parts typically uses simplistic geometrical demands for design rules [7] or draw direction [8], and does not consider process steps as mould filling and solidification or the relationship between microstructure and local mechanical properties. Other works consider homogeneous material behaviour for the elasto-plastic behaviour while specific material properties as ultimate tensile strength are heterogeneously scaled based on heat extraction related parameters as solidification time from casting process simulations [9]. The relevance of considering manufacturing aspects as draw direction to generate geometries suitable for casting in topology optimisation of cast parts has been reviewed [10], but the heterogeneous material behaviour of castings has not been addressed. No previous method for cast parts has been found where heterogeneous material behaviour is used, or casting process simulations fully integrated into the structure optimisation to generate and incorporate geometry-dependent microstructure-based elasto-plastic stress–strain behaviour into the optimisation routine.

For polymeric parts, integrated simulation methods to predict heterogeneous elastic material behaviour have been developed for semi-crystalline polymeric parts [11] and short fibre composites [12]. For glass-fibre reinforced materials, a method to identify process parameters (e.g. gate location) to obtain the predicted optimal fibre-orientation for given conditions has been proposed [13]. However, a structural optimization method for injection moulded polymers with full integration of heterogeneous anisotropic non-linear material behaviour based on predicted glass-fibre orientation has not been found in the literature.

In a traditional sequential product realisation process, where the development moves from designer to structural analysis to production as illustrated in Fig. 1a, the knowledge and information from the engineers within the different disciplines enters the product realisation chain at different subsequent steps of the process. The amount of knowledge that can be added in each step down the process decreases, since the time and possibilities to introduce changes to the product continuously decreases. This approach tends to lead to a lot of design iterations and loop-backs, since important changes to ensure structural integrity or enable manufacturability are discovered late, causing long lead times and high costs.

In the present work, a new method for microstructure-based structural optimization of castings is presented. *Microstructure-based* implies that in each iteration of the optimization loop microstructural features are predicted using a manufacturing process simulation and considered in the structural analysis. A knowledge-based engineering (KBE) perspective is adopted to identify the workflow in the optimization loop, see Fig. 1b. The concept of Knowledge Based Engineering (KBE) is further described and reviewed elsewhere [14], and has previously been applied on system levels e.g. aircraft design [15] and the automotive area [16]. The current methodology aims to promote and enable the focus on multidisciplinary product knowledge and collaboration at early stages of the product realisation process. A methodology which takes local material behaviour into consideration is relevant for engineers within engineering design, materials science, production and CAE, and will enable new insights into the interdependence between disciplines as design and manufacturing.

2. Methodology

In the current framework, a parameterised CAD-model serve as the starting point (process step 1 in Fig. 2), where geometrical features, parameters and constraints are introduced to represents design intent and the geometrical limitations for the part. Topology optimization methods based on density-scaling within a black-box geometry are highly useful to generate initial design concepts to serve as a starting point for designers, but in the context of manufacturability they have clear limitations. Such a volume with density variations is not physically achievable, and the CAD-representation can't be directly used for further simulations or analyses without manual or numerical interpretation [17]. Using the parametric model, fully defined solid CAD-models are here rather updated than generated for each alternative design. The loop as presented in Fig. 2 is in other words preceded by the utilization of topology optimization to develop the parameterized CAD-model. These parameterized CAD-models can allow topology changes by suppressing or activating various geometrical features and hence allow for the evaluation of a set of topological suggestions. The benefit of utilizing CAD-models in this manner is that it enables direct integration of manufacturing process simulations into a structural optimization routine, and in addition the result after optimization is a solid CAD-model which can be directly used for detailing and subsequently serial production.

The suggested approach is implemented into a prototype software which is based on the automation of a set of engineering actives, as illustrated in Fig. 2 forming an optimization loop. The different engineering tasks includes *Update Geometric Model, Generate Mesh, Execute Manufacturing Simulation, Render FEM-model with Local Material Data, Execute Simulation, Analyse Output.* These tasks are controlled and executed using a design automation system based on knowledge-objects. The modules and the control system are described in detail in the following sections.

2.1. Automation using knowledge objects

To assist the implementation of knowledge into engineering software, object-oriented technology has been adopted into so called knowledge objects. Knowledge objects may consist of e.g. geometry parameters (wall thicknesses, distances, radii, angles, spatial limitations etc.), material parameters (material or alloy type, chemical composition etc.), performance objectives (stresses and strains, vibrations etc.) or other types of knowledge and demands (legislation, cost, etc.).

Knowledge objects have previously been applied to automate the manufacturability analysis process for draw bending of circular tubes, to automatically setting up and executing non-linear FEA-simulations, while handling multiple types of extrusions and making the interpretation of the simulation results [18]. In the mentioned draw bending system the simulations were performed using CATIA™ for geometry modelling and meshing, and LS-DYNA™ to process the simulation. In 2014 a new system was developed combing SolidWorks™, ANSA™ and LS-DYNA™ to simulate car collisions focusing on keeping roof racks at top of the roof [19]. That system made the modelling of FEA-related features possible so that design engineers could execute the simulations while the FEA-specialist could focus on developing the simulation processes. In this paper a combination of these two systems, see Fig. 3, serves as the base to engineering automation through knowledge objects.