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A Framework for the Computer-Aided Planning and Optimisation of Manufacturing Processes for Components with Functional Graded Properties

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Abstract
In this contribution a framework for the computer-aided planning and optimisation of functional graded components is presented. The framework is divided into three modules – the "Component Description", the "Expert System" for the synthetisation of several process chains and the "Modelling and Process Chain Optimisation". The Component Description module enhances a standard computer-aided design (CAD) model by a voxel-based representation of the graded properties. The Expert System synthesises process steps stored in the knowledge base to generate several alternative process chains. Each process chain is capable of producing components according to the enhanced CAD model and usually consists of a sequence of heating-, cooling-, and forming processes. The dependencies between the component and the applied manufacturing processes as well as between the processes themselves need to be considered. The Expert System utilises an ontology for that purpose. The ontology represents all dependencies in a structured way and connects the information of the knowledge base via relations. The third module performs the evaluation of the generated process chains. To accomplish this, the parameters of each process are optimised with respect to the component specification, whereby the result of the best parameterisation is used as representative value. Finally, the process chain which is capable of manufacturing a functionally graded component in an optimal way regarding to the property distributions of the component description is presented by means of a dedicated specification technique.

Keywords: Manufacturing Process Planning, Functionally Graded Components, Expert System, Specification Technique, Sustainable Production

INTRODUCTION

Functional gradation denotes a continuous distribution of properties over at least one of the spatial dimensions of a component made of a single material. This distribution is tailored with respect to the intended application of the component [1].

Application areas for the use of functionally graded components can be found e.g. in the automotive industry. Car interior door panels for instance are usually plastic materials that are supposed to absorb the impact energy of a lateral crash to a certain extent. The resulting deformation however must in no case lead to an injury of the passengers. To achieve a desired deformation behaviour it is necessary to assign exactly defined material properties to specific locations of the door panel. By functional gradation, e.g. of the hardness, the functionality of the component can be considerably extended.

Components with functionally graded properties provide a resource-conserving alternative for modern composite materials [1] and therefore offer high potential to achieve a sustainable production. However, the production of such components requires complex manufacturing process chains [1]. For that purpose in the next section an exemplary manufacturing process chain will be used to demonstrate our approach. This process chain consists of heating-, cooling-, and forming process steps and enables the gradation within the component during the moulding process. To realise the full potential of functional gradation, a computer-aided framework for the planning and optimisation of those manufacturing chains will be described in section three, whereupon the optimisation by empirical models will be presented in section four. Section five summarises the approach and identifies the significant research challenges for the future.

EXEMPLARY MANUFACTURING PROCESS CHAIN

Self-reinforced polypropylene composites provide a good basic material for the production of components with functional graded properties [2]. Essentially the locally varying processing forces and temperatures during the compression moulding process alter the material structure of the polypropylene composites towards functional gradation. This self-reinforcement

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is induced by melt and solid phase deformations in the macromolecular orientation of the polymer [3].

Especially highly oriented fabrics, fleeces or films [4] serve as raw material for the self-reinforced composites since the self-reinforcement and its macromolecular orientation cannot be directly applied to the structural composites. The according raw materials are layered and hot compacted into thermo-mechanically graded layered composites using varying temperatures and pressures [5].

Due to the numerous processing influences during the IR-preheating process step and the compression moulding process, the self-reinforced composites react extremely process sensitive. Thermal gradation is already applied during the IR-preheating sequence by means of masking the radiation panel halves with masking sheets. These shield the area of fabric or fleece composite located beneath it from heat. Subsequently the pre-tempered textile composite is put into a pressing unit in which the hot compaction process takes place. The shaping tool was particularly designed for thermo-mechanical gradation and can be tempered differentially, so that the tool halves can be tempered independent of one another. Furthermore a pressure reduction of up to 30% results on the slanted sides of the triangular geometry in comparison to the flat parts of the tool. This complex processing step requires a careful balancing of the process parameter settings, especially regarding to the thermo-mechanical gradation.

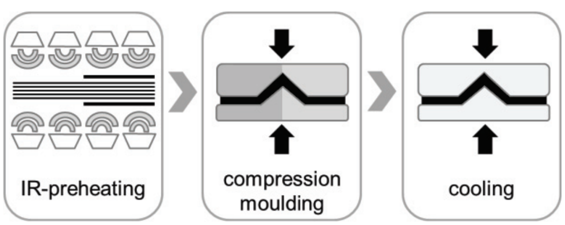

FIGURE 1 – Manufacturing process chain of self-reinforced polypropylene composites by the process steps: IR-preheating, compression moulding and cooling.

Figure 1 shows an exemplary manufacturing process chain for self-reinforced polypropylene composites.

MANUFACTURING PROCESS PLANNING FOR COMPONENTS WITH FUNCTIONAL GRADED PROPERTIES

The exemplary manufacturing process chain of self-reinforced polypropylene composites with functional graded properties is characterised by strong interdependencies between the component and the manufacturing processes as well as between the process steps themselves. These interdependencies are typical for the manufacturing of graded components and need to be considered. Therefore a framework for the planning and optimisation of manufacturing process chains has been developed. The framework integrates several methods, tools and knowledge obtained by laboratory experiments in which the concept of functional gradation has been analysed. The planning process within the framework is continuously assisted by the three modules "Component Description", "Expert System" and "Modelling and Process Chain Optimisation" [1].

The CAD model of the component and the component properties provide the input information for the planning framework. Based on this information, alternative process chains for the manufacturing of the component are synthesised by means of the framework. After this, the process parameters of each process chain are optimised based on empirical models. The best process chain is described with a dedicated specification technique for production systems in the last step of the planning process (cf. Figure 2), [6].

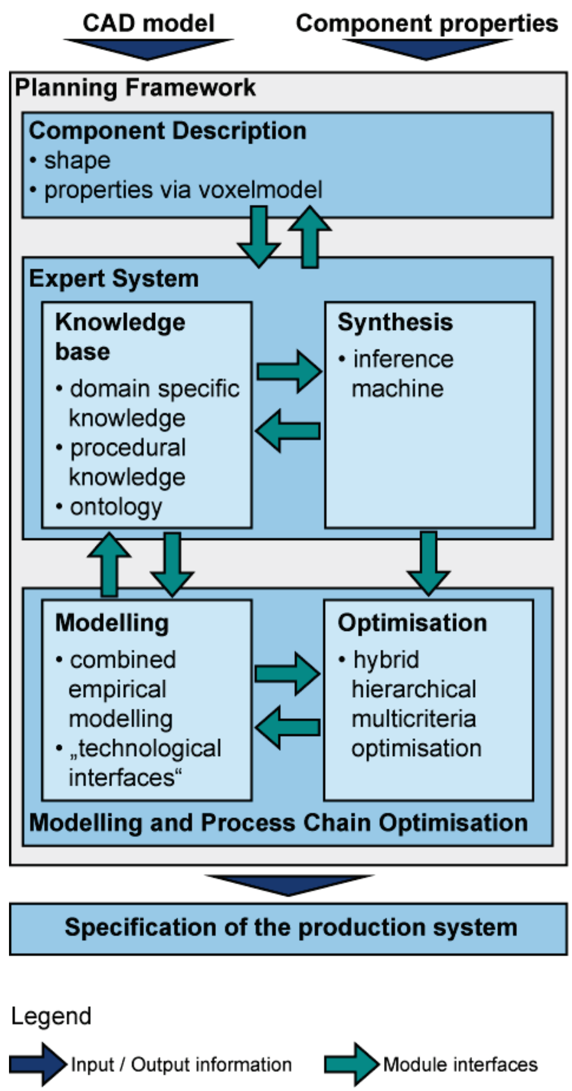

FIGURE 2 – Planning framework for the computer-aided planning and optimisation of components with functional graded properties.

The **Component Description** module allows the desired graded properties to be integrated into the CAD model of the component. The model usually consists of geometric features (e.g. cylinder or disc), which will be extracted after importing the CAD model. In the next step, these features are analysed to pre-select reasonable gradients according to the geometry of the whole component. This pre-selection increases the efficiency for describing the intended gradient since the manufacturing planner can directly provide the desired properties by modifying the parameters of the gradients proposed. If the CAD model does not contain geometric features or the user does not want to use one of the pre-selected gradients, the component is divided into volume elements. These volume elements, so called voxels, allow the component to be locally addressed and can be used as supporting points for the function-based integration of the component's graded properties [1], [7].

Based on the enhanced computer-aided design model, the **Expert System** synthesises several alternative process chains for manufacturing the component. Therefore all the manufacturing process steps of the knowledge base are filtered with regard to the component description such as material, geometry or the intended graded properties (e.g. hardness or ductility). That's why the content of the knowledge base is structured by an ontology, which classifies the process steps basically upon their characteristics and connects the information via relations between the content elements. An inference machine is applied for the purpose to draw conclusions from the ontology. These conclusions provide the basic information for connecting the process steps of the knowledge base during the synthetisation of reasonable manufacturing process chains according to the enhanced CAD model of the component description module [1].

The exemplary manufacturing process chain for self-reinforced polypropylene composites is for instance characterised by the fact that the initial material temperature, which is adjusted during the IR-preheating process has a strong influence on the mouldability of the component. Those and all interdependencies mentioned above need to be considered during the pairwise evaluation of the process steps to ensure the compatibility of the synthesised manufacturing process chains. All process chains with incompatible process steps are disregarded. The optimisation of the manufacturing process chains is described in the next section.

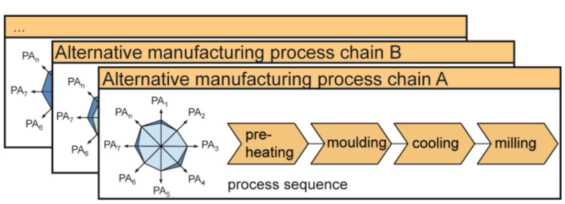

FIGURE 3 – Set of alternative process chains given by the planning framework.

Thus the result of the Expert System module is a set of several alternative process chains which are capable of producing the component (cf. Figure 3), [1].

The process parameters of a preferred set of manufacturing process chains are optimised by means of the **Modelling and Process Chain Optimisation** module, [1]. To accomplish this, predictions of empirical models based on several experiments, measurements and simulations of research samples provide a convenient solution space (cf. [8]). Therefore modern empirical modelling techniques combined with a hybrid hierarchical multi-objective optimisation are used, which will be described in more detail in the following section.

Process Chain Optimisation by Empirical Models

The knowledge about the relationship between the process parameters and the process outputs needs to be formalised for an automated optimisation. Since empirical models are based on a black box structure and are efficient to evaluate, they provide the basis for the process chain optimisation. In order to provide feasible surrogates for the actual processes, the empirical models have to describe the output of the processes with sufficient precision. The surrogate model selection, however, is a challenging task, due to a large number of modern statistical learning techniques with individual strengths and drawbacks. For components with graded properties, DACE models have proven to show a very good fit and prediction quality [9], [10].

With a surrogate model for each process, entire process chains can be simulated. Figure 4 exemplarily shows a process chain for the functional gradation of polymers. The first process is a stretching process for polycarbonate films. The process can be controlled by parameters like rotation speed of the roll units, annealing temperature or stretching temperature. With the information stored in the surrogate models, the behaviour of the process responses like Young's modulus or tensile strength can be predicted for every process parameter setting. This information is then passed on to the next process step. The transferred properties, which strongly influence the following processes, are called Technological Interfaces. The next step in the example is a heating process. By varying the process parameters like heating time and heating temperature, the temperature of the material can be controlled. Through differential spatial heating, a thermal gradation can be achieved. Hence, the material temperature acts as Technological Interface between the second and third process step. An optimised distribution can assist in refining the graded properties in the subsequent compression moulding process. Thus, the interface material temperature is considered together with the process parameters pressing time, pressure and pressing temperature in order to predict the gradation of properties like damping, deformation or thickness after the moulding.

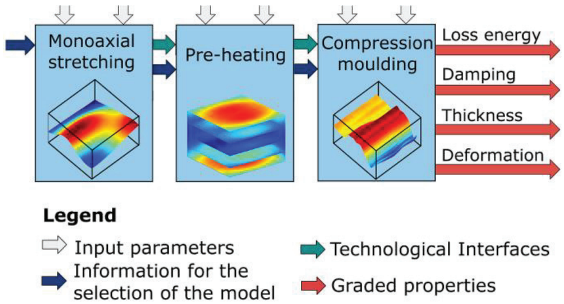

FIGURE 4 – Exemplary process chain for the functional gradation of self-reinforced polypropylene composites.

Based on the connected empirical models, the process chain optimisation is performed. The optimisation is performed in a hierarchical manner. It starts with the last process of the process chain, i.e., compression moulding in the example of Figure 4. This process is optimised according to the desired graded properties including the Technological Interfaces. If the process is not able to sufficiently comply with the specifications, the process chain is discarded. If it is possible to find a good compromise, it needs to be checked, if the required intervals of the Technological Interfaces can be provided in the preceding process. This process is then optimised to provide the required values of the Technological Interfaces to its predecessor. This procedure continues until all process parameters are obtained. At the end of this procedure, the optimum parameters and property gradations are approximated for all manufacturing process chains.
Based on these values and information about the operating efficiency of the processes, the best alternative can be selected. This process chain is described using a dedicated specification technique which is based on a process sequence and a resource diagram [11].

CONCLUSION AND OUTLOOK

Components with functional graded properties offer an innovative and sustainable approach for customisable products. Therefore a comprehensive framework for the computer-aided planning and empirical model-based optimisation of components with functional graded properties has been presented and demonstrated with an application example.
Future work includes the enhancement of the knowledge base with additional manufacturing processes and interdependencies as well as the adjustment of the ontology. In addition, the inference rules of the expert system have to be expanded to realise the synthetisation of more complex manufacturing process chains and also their pairwise evaluation. The Expert System of the framework is able to automatically synthesise manufacturing process chains for the production of a component with functionally graded properties, however the final selection of the best process chain for the specific production objective must still be conducted manually. But it is not always obvious which alternative fulfils all the requirements in the best way. The Analytic Hierarchy Process (AHP, cf. [12]) may offer an effective method to handle the highly diverse characteristics of the decision criteria while not overstraining the decision process with data acquisition and examination.

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