Kurzfassung

In der Dissertation wird die Imprägnierung eines Verstärkungseinlegers aus Kohlenstofffasern durch ein Sheet Moulding Compound (SMC) untersucht. Dabei besitzt der Kohlenstoffstruktureinleger zu Beginn keine Vorimprägnierung. Stattdessen erfolgt die Durchtränkung der Kohlenstofffasern durch die Harzbestandteile des SMC-Materials während des Fließpressprozesses. Durch die Kombination des SMC-Materials mit einem Kohlenstofffaserstruktureinleger, welcher mit dem Tailored Fibre Placement-Verfahren hergestellt wird, entsteht ein sogenannter Hybrid SMC Verbundwerkstoff, welcher sich durch eine hohe Designfreiheit, gute mechanische Eigenschaften und gleichzeitig hohen Produktionsraten auszeichnet.
Das Hauptziel dieser Dissertation ist die Entwicklung eines Imprägnierungsmodells für Hybrid SMC Verbundwerkstoffe. Dabei sagt das Imprägnierungsmodell unter Berücksichtigung der Halbzeug- und der Prozesseigenschaften den verbleibenden Porengehalt voraus. Die Imprägnierung des Struktureinlegers ist von der Viskosität, des Prozessdrucks, der Permeabilität und der Dicke des Struktureinlegers abhängig. Dabei ist die Viskosität ein entscheidender Faktor für die Faserimprägnierung, da sie sowohl von der Temperatur als auch von der Zeit abhängig ist. Zum einen bestimmt die Temperatur den Gelpunkt, da nach Überschreiten dieses Punktes keine weitere Durchtränkung der Kohlenstofffasern möglich ist. Zum anderen wirkt sich die Zeit- und Temperaturabhängigkeit auf das generelle Fließverhalten aus, welches üblicherweise für SMC-Materialien hochviskos ist. Thermische Analysemethoden werden daher umfassend eingesetzt, um den Gelpunkt und die Fließeigenschaften zu bestimmen. Auch die Bestimmung der weiteren Parameter fließt in das Imprägnierungsmodell ein. Auf Basis eines Ansatzes aus der Fluiddynamik wird das Imprägnierungsmodell entwickelt, um die Fließfront innerhalb des SMC-Materials während des Fließpressens zu verfolgen. Parallel werden experimentelle Untersuchungen an Hybrid SMC Verbundwerkstoffen umgesetzt und der Porengehalt durch den Einsatz von mikroskopischen, bildgebenden Methoden bestimmt. Die Auswertung erfolgt durch die Anwendung Methoden aus der Statistik, um die signifikanten Parameter zu identifizieren. Zudem wurden die experimentell ermittelten Porengehälter zur Validierung des Imprägnierungsmodells eingesetzt. Insgesamt führten die Untersuchungen zu einem Imprägnierungsmodell mit hoher Genauigkeit. Bei über 82 % aller Messungen stimmt das analytische Imprägnierungsmodell mit einer hohen Genauigkeit (Die Abweichungen sind geringer als 5 %) überein.

Abstract

This thesis deals with the fibre impregnation of a carbon fibre reinforcement by a sheet moulding compound (SMC). In the beginning, the carbon fibre reinforcement has no impregnation. Instead, the impregnation of the carbon fibre is performed by the resin within the SMC material during compression moulding. The combination of a SMC material and a carbon fibre reinforcement, which is made by the Tailored Fibre Placement technology, leads to a Hybrid SMC composite, which is characterized by a high design freedom, good mechanical properties, and high production rates at the same time.

The main objective of this study is the development of an analytical impregnation model for Hybrid SMC composites. The impregnation model predicts the final void content with regard to the properties of the semi-finished products and the process implementation. The fibre impregnation is influenced by the viscosity of the SMC material, the processing compression, the permeability, and the thickness of the carbon fibre reinforcement. Among all these parameters, the viscosity is an essential factor for the fibre impregnation, because it is dependent on the temperature and the time. First, temperature has an impact on the gelation point. After passing the gelation point, no more fibre impregnation can be performed. Second, the time- and temperature-dependency acts on the general flow characteristics which is typically high-viscous for SMC materials. Therefore, thermal analysis is comprehensively used to determine the gelation point as well as the flow characteristics of the SMC material. The other influencing parameters are determined to support the fibre impregnation model. An impregnation model is developed by a fluid dynamic's approach to track the flow front particles within the SMC material during compression moulding. At the same time, experiments are realized and the void content is determined by using microscopic analysis of the Hybrid SMC composites. The experiments are evaluated by the consequent use of statistical instruments to find the most significant parameters. Furthermore, the evaluated void contents of the experiments are used as a validation for the impregnation model. All in all, the investigations have led to an analytical impregnation model with a high accuracy. A deviation of 5 % for more than 82 % of the specimens was achieved.

1 Introduction

1.1 Motivation

Productivity is one of the most challenging factors in the development of fibre reinforced plastics (FRP). It is defined as the ratio between the output and the input of a good [1]. Taking FRP into account, the output can be frequently found in the low part weight and the excellent mechanical properties at the same time. However, the dimensioning of FRP is more complex due to the anisotropic fibre properties. In addition, especially carbon fibres are more expensive due to their extensive production process. Therefore, the use of FRP is often hindered. This is why it is important to find new ways to increase FRP productivity and to find fields in which the use of FRP can have a significant impact.

Hybrid solutions are an appropriate method to increase the FRP productivity. A hybridization is the combination of at least two materials or processes to use the advantages of both [2]. In the ideal case, the specific disadvantages of the individual materials are eliminated due to the combination. For example, the development of intrinsic hybrids is preferred which are characterized by one-step processes which do not require any subsequent joining processes [3]. In 1984, Tompkins and White has developed the design rule "The right material at the right place" which links to the approach of hybridization [4]. This approach has been asserted oneself in the engineering environment, especially in the automotive industry, which demonstrates the success of the hybrid method of construction [5]–[7].

The manufacturing of Hybrid Sheet Moulding Compound (Hybrid SMC) composites is a promising technology to realize powerful composites with an economic production process at the same time. It synergises a SMC material and

a continuous fibre reinforcement. In this case, the continuous carbon fibre reinforcement is manufactured with the Tailored Fibre Placement (TFP) technology. This technology allows the production of the near-net shape and load-path optimized designs. Therefore, the production is characterized by a good material efficiency. Due to the carbon fibre reinforcement, the mechanical properties can be significantly increased in comparison to pure SMC materials [8]. Moreover, short cycle times for the manufacturing of SMC parts can still be achieved. From an ecologic perspective, the compression moulding of SMC materials is an energy-efficient production process in comparison to other FRP manufacturing technologies [9]. Metallic inserts can be easily implemented to allow a simple joining for other components. This brief description of the advantages illustrates the great potential of Hybrid SMC composites.
However, new hybrid material solutions require an accurate safeguarding of the composite quality. In the case of the manufacturing of Hybrid SMC composites containing a carbon fibre reinforcement, one of the most important quality characteristic is the impregnation of the reinforcing fibres. In general, the fibre impregnation of carbon fibre textiles within Hybrid SMC composites is a challenging task which strongly differs to the fibre impregnation of other thermoset processing. Especially the high viscosity and the low permeability due to the use of a carbon fibre reinforcement as well as the expected high fibre volume content hinder the fibre impregnation. An incomplete fibre impregnation would lead to a decreased fibre support which finally results in reduced mechanical properties [10]–[12]. Therefore, it is important to ensure the impregnation of the reinforcing fibres to avoid the formation of voids and to avoid premature failure of the hybrid composite.

1.2 Objective

The objective of this study is the development of an analytical model to predict the fibre impregnation of dry continuous fibre reinforcements by using conventional SMC materials as resin carriers. It considers the important material and process characteristics which significantly influence the fibre impregnation of continuous carbon fibre reinforcements while compression moulding. The analytical model is tested through additional experiments.

The individual results can be summarised as follows:

- Characterisation of Hybrid SMC containing TFP reinforcements and SMC
- Formulation of a methodology for the development of an impregnation model
- Determination of the chemo-rheological behaviour of SMC
- Development of an impregnation model
- Experimental investigation to evaluate the key parameter

2 Fundamentals of Sheet Moulding Compounds

Compression Moulding of Sheet Moulding Compounds is one of the oldest manufacturing techniques for processing fibre reinforced plastics. By 1947, a composite body of a car, mostly based on SMC, has already been developed and tested for the first time which finally led to the Corvette C1 [13]. Today, new fields and applications are implemented through the use of SMC in the automotive industry. Recently, Lamborghini has searched for a lightweight material for the manufacturing of a rear wing of the model Huracan Performante. Besides the traditional structural and cosmetic requirements, the desired material has to be formed to a hollow structure. This hollow structure is used for the active wing system to ensure maximum down force or either minimum drag. The compression moulding of SMC enables the manufacturing of composite structures to fulfil these requirements due to high design freedom [14]. But not only the supercar manufacturers use carbon fibre SMC materials. Recently, Toyota has presented their new method for the manufacturing of a rear door frame made out of carbon fibre SMC [15]. It indicates that the technology even enables large scale carbon fibre components in non-luxury passenger cars (Figure 1, right).

However, just 21 % of the annually produced SMC materials are used in the automotive industry. Further important industries are the electrical/electronic, the aviation/defence, and the construction sector (*Figure 2*) [16]. In Europe, the annual growth rate of SMC is 2.2 % per year. More or less, this growth rate was constant in the last years [17]. In the next ten years, the compound annual growth rate (CAGR) will rise to 6.0 % (Figure 2) [16]. Together with material-related BMC, the total amount of the moulding compounds is 280.000 tons per year. Therefore, it is the most frequently used manufacturing method for processing glass fibres to FRP [5]. An ideal production rate for using SMC is between 10.000 and 80.000 parts per year which is determined by the short cycle times of 2 – 5 minutes [18].

Figure 1. Rear wing of the Lamborghini Huracan Performante (left) [19]*; Rear door frame of the Toyota Prius PVH [15]*

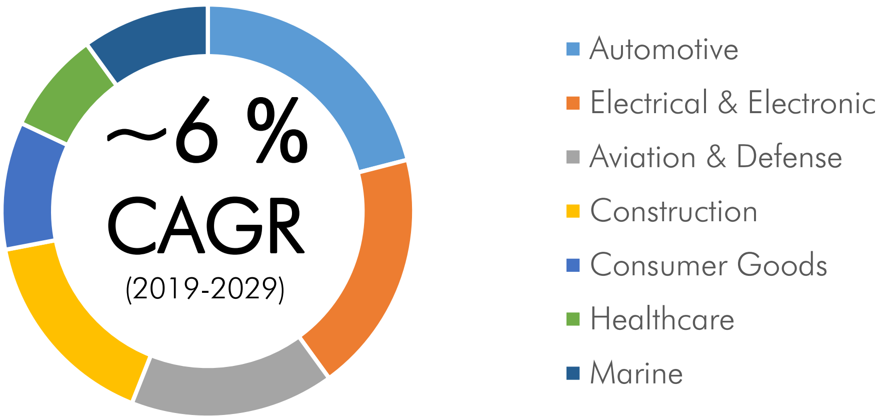

Figure 2. Sheet Moulding Compounds market by end use, 2019 [16]

In the following, the general characteristics of SMC materials are presented. At first, a description of the individual compositions of SMC materials is made. The individual compositions are processed with an impregnation lane for the manufacturing of a semi-finished SMC which is required for the subsequent compression moulding process. In addition, the thickening and curing reactions of unsaturated polyesters are explained because an UP-based SMC material is used in this study. Further information is given about the types of reinforcements. These are predominantly glass fibre reinforcements in the shape of long fibres but other fibres were already used or investigated in the past.