Kurzfassung

Gegenwärtig stellen die hohen Stückkosten das wesentliche Hemmnis für die Marktdurchdringung endlosfaserverstärkter Bauteile dar. Das umfassende Ziel dieser Arbeit war daher die Senkung der Prozesskosten durch die Steigerung der Prozessgeschwindigkeit. Ansatzpunkt bildete der zeitintensive Imprägnierungsvorgang, welcher durch die Verwendung einer in orthogonaler und planarer Richtung ablaufenden 2D-Imprägnierung optimiert wurde.

In der Analysephase wurden grundlegende Untersuchungen mit einer semi-kontinuierlich arbeitenden Intervallheißpresse durchgeführt. Dabei zeigten sich komplexe Wechselwirkungen zwischen inhomogenen Temperatureinstellungen, vorliegender Druckverteilung, planarem Fließverhalten des Polymers und der resultierenden Imprägnierungsqualität. Als vorteilhafte Prozessbedingung wurden Polymerfließvorgänge in Richtung der offenen seitlichen und vorderen Werkzeugkante identifiziert, welche durch die bei höheren Randtemperaturen vorliegende Druckverteilung begünstigt werden. Mit einem eigens dafür entwickelten Presswerkzeug ist die prinzipielle Vorteilhaftigkeit einer Kombination aus orthogonalem und planarem Polymerfließen auf die Imprägnierungsgeschwindigkeit nachgewiesen worden. Die durchgeführte Parameterstudie verdeutlicht das Potential durch die Verkürzung der Imprägnierungsdauer um 33 %. Bei der Analyse der Druckprofile ist für den Übergangsbereich von der Heiz- zur Kühlzone ein signifikanter Druckabfall festgestellt worden. Um die dadurch bedingte Dekonsolidierung während der Solidifikation zu verhindern, wurde ein an das Schwindungsverhalten des Laminats angepasstes Werkzeugdesign für den Übergangsbereich entwickelt. Dadurch konnte die Reduktion des applizierten Prozessdrucks verhindert und die Verschlechterung der Organoblechqualität während der Abkühlung ausgeschlossen werden. Für die Modellierung des Imprägnierungsvorgangs wurde das B-Faktor-Modell von Mayer durch die Integration der vom Verarbeitungsdruck abhängigen Sättigungspermeabilität erweitert. Dadurch wird die Abbildung von Prozessen mit nicht konstantem Prozessdruck ermöglicht.

Die Ergebnisse der Arbeit bilden die Grundlage für die effektive Prozessgestaltung durch ein materialspezifisches Anlagendesign und die Wahl vorteilhafter Prozessparameter von der Einzel- bis zur Serienproduktion.

Abstract

Due to the good lightweight potential of fiber reinforced composite materials, there is an increasing interest in using multifarious applications across the whole mobility industry. Presently, in mass scale production only non-structural parts produced with injection molding technology are able to compete with their metal counterparts economically. For high performance composite parts containing endless fiber reinforcement, material costs and process costs are still too high. Thus, the motivation for this thesis was to overcome this economic disadvantage by utilizing cost reduction potentials, which are based on process optimizations.

The process optimization has been demonstrated with the Continuous Compression Molding machine of the IVW GmbH. This machine offers the possibility to use diverse 2D-temperature profiles. Hence, the laminate is exposed to an inhomogeneous temperature distribution during processing. Due to these conditions polymer flow might be generated in-thickness and in-plane direction at the same time (2D-impregnation). This offers the chance for an increase of the impregnation speed. Thus, the principle purpose of the thesis was the analysis and the optimization of the organic sheets production with respect to an improved process performance by using a 2D-impregnation.

In the first step a comprehensive analysis of the process conditions and their interactions has been carried out. Therefore a laminate consisting of polypropylene and a glass fiber textile has been used. In order to measure the temperature and pressure distribution during the production process, thermocouples and pressure sensors have been placed in the laminate. Additionally, in-plane polymer flow was detected by incorporated polymer yarns, which had a different color compared to the matrix material. The evaluation of the impregnation quality with regards to the effect of different parameter settings has been carried out by micrographs of polished cross sections.

The analysis revealed an inhomogeneous pressure distribution inside the pressing tool for all evaluated temperature settings. In general, the pressure distribution could be characterized by an increasing pressure from the inlet and the lateral tool edges to the center of the tool. In case of using lower (higher) temperature at the lateral edges, the pressure is increased (reduced) at these areas. Because of this, for lower (higher) temperatures at the lateral edges of the tool, the pressure gets more homogeneous in cross (longitudinal) direction. This also affected the in-plane polymer flow as well as the impregnation speed significantly. Finally, a correlation between the used temperature setting, the pressure distribution, the polymer flow and the resulting impregnation speed was identified:

- Lower temperatures at the lateral edges are leading to an increased pressure at the edges. Therefore the polymer flow is aligned towards the center of the tool and the sideways air permeability is reduced. These settings are leading to a reduced impregnation speed in cross direction.
- For isothermal temperature settings and higher temperatures at the edges, the pressure is mainly focused on the center of the tool. Thus, the polymer flow is aligned towards the inlet and the lateral edges. This strongly supports the impregnation process. Thus, the impregnation speed is increased in process direction as well as in cross direction.

Based on these findings, a special pressing device has been developed in order to evaluate the 2D-impregnation elementarily. The pressing device enables various process conditions, which are leading to in-thickness and in-plane 2D-impregnation. Furthermore, the upper and the lower tools are equipped with glass inserts, so that observation of the impregnation process was possible just in time. This significantly reduced the effort for the evaluation of the laminate quality and enabled the detailed analysis of the polymer flow during the impregnation. With regards to the impregnation speed, the influence of different parameter settings has been examined with a parametric study. In the end, the benefit of a 2D-impregnation has been approved. For the best configuration, the impregnation process has been accelerated by 33 %. Thus, 2D-impregnation is important for the improvement of the economical competitive situation of endless fiber reinforced thermoplastic composites. As a further result, advantageous tool geometries have been derived for the Continuous Compression Molding machine. Due to the adaption of the tool cavity at the inlet area, in-plane polymer flow and the displacement of entrapped air could be improved and the impregnation speed is increased.

Furthermore, the analysis of the pressure distribution disclosed a rapid pressure drop in the transition region from the heating to the cooling area. This effect could be traced back to the shrinkage of the polymer during cooling. Thus, this finding is of major importance for the quality of organic sheets, because cooling under low pressure might evoke deconsolidation. A theoretical examination of the thermodynamic states for the entrapped air has been carried out. It was shown that void growth has a big influence on laminate deconsolidation in the transition region. In order to eliminate this disadvantage, the tool design of the transition region has been modified. In a first step, the specific shrinkage behavior of the laminate has been characterized for the temperature range between 20 °C and 190 °C. Afterwards, the tools geometry has been adapted to the laminate shrinkage. The effectivity of the modifications has been proved by additional pressure measurements and by the calculation of resulting thermodynamic states. Consequently, the shrinkage has been compensated, the pressure drop has been minimized and deconsolidation was avoided.

The last chapter of this thesis focused on the modelling of the thermoplastic impregnation process under non-isobaric process conditions. Therefore, the B-Faktor model of Mayer has been used, because it considers all effects of the thermoplastic impregnation implicitly. But within a theoretical contemplation it was shown, that the model cannot be used for non-isobaric process conditions. Thus, an extension has been developed, which includes pressure-dependent permeability values of the reinforcement textile. Owing to this extension, the comparison of different parameter settings as well as the definition of new process parameters (temperature, pressure, and time) is possible. Thus, the model enables the specific design of new, efficiently working machines for large scale production.

Taken together the developed process optimizations and the incorporated model extension are of major importance for the reduction of process costs for organic sheets. Furthermore, the results are the basis for the development of new efficiently working machinery equipment and the process optimization for different fiber reinforced materials. Thus, the presented thesis plays an important role for the increase of market share for parts made of endless fiber reinforced composite materials.