Kurzfassung

Die Herstellung von hochleistungs Kunststoff Verbunden für Strukturbauteile erfolgt in der Automobilindustrie mittels Resin Transfer Molding (RTM), wobei die Kosten für die Bauteile sehr hoch sind. Die Kosten müssen durch Prozessoptimierungen deutlich reduziert werden, um eine breite Anwendung von faserverstärkten Kunststoff Verbunde zu ermöglichen. Prozesssimulationen spielen hierbei eine entscheidende Rolle, da zeitaufwendige und kostspielige Praxisversuche ersetzt werden können.

Aus diesem Grund wurden in dieser Arbeit die Potentiale der simulativen Abbbildung des RTM-Prozesses untersucht. Basis der Simulationen bildete eine umfangreiche Materialparameterstudie bei der die Permeabilität, von für die Automobilindustrie relevanten Textilhalbzeugen im ungescherten und gescherten Zustand, untersucht wurde. Somit konnte der Einfluss von Drapierung bei der Fließsimulation evaluiert werden. Zudem wurde eine neue Methode zur Ermittlung der zeit-, vernetzungs- und temperaturabhängigen Viskositätsverläufe von hochreaktiven Harzsystemen entwickelt und angewendet. Die Fließsimulationsmethode wurde zunächst erfolgreich an einem ebenen Plattenwerkzeug validiert, um zu zeigen, dass die ermittelten Materialparameter korrekt bestimmt wurden.

Zur Validierung der Simulation wurde ein komplexes Technologieträgerwerkzeug (TTW) entwickelt. Die Auslegung der Temperierung wurde mittels Temperiersimulationen unterstützt. Untersuchungen an markanten Kantenbereichen, wie sie bei Automobilbauteilen häufig auftreten, haben gezeigt, dass bei Kantenradien < 5 mm ein Voreilen des Harzsystem zu beachten ist. Zudem konnte mittels verschiedener Angussleisten, der Einfluss verschiedener Angussszenarien untersucht werden.

Mit Hilfe von Sensoren im TTW wurden die Prozessdaten protokolliert und anschließend mit den Simulationen verglichen. Die Ergebnisse zeigen, dass die simulative Abbildung des Füllprozesses bei einem komplexen RTM-Werkzeug, trotz einer Vielzahl an Prozesseinflüssen, möglich ist. Die Abweichungen zwischen der Simulation und dem Versuch lagen teilweise unter 15 %. Die Belastbarkeit der ermittelten Permeabilitäts- und Viskositätswerte wurde dadurch nochmals bestätigt. Zudem zeigte sich, dass die Angussleistenlänge einen signifikanten Einfluss auf die Prozesszeit hat, wohingegen der Angussleistenquerschnitt eine untergeordnete Rolle spielt.

Abstract

In the automotive industry, continuous fiber reinforced polymer composites (CFRPC) are often manufactured using resin transfer molding (RTM). The costs of the components produced by this technique are very high compared to equivalent metal parts. To make the CFRPC competitive, the costs have to be lowered by optimizing the RTM process chain in terms of cycle time and material respectively energy efficiency. This goal can be achieved by replacing time consuming trial-and-error procedures through standardized process simulation.

In this work the potential, validity, and reliability of RTM filling simulations were investigated. As a starting point a comprehensive permeability characterization study of automobile-relevant textiles was performed. The permeability of sheared and unsheared glass fiber weaves and carbon fiber fabrics was examined. The results built the basis for considering the influence of draping in the RTM simulation. Moreover, a new method was developed to measure the viscosity of highly reactive resins with respect to time, under process-oriented conditions. Resin is injected into a cavity with a reference material (permeability known) and the flow front progression in the cavity is monitored. Knowing the time-dependent flow front progression, it is possible to calculate the viscosity development due to time. Experimental parameters were set to match the process conditions of the RTM process, leading to an exact description of the development of the resin viscosity in the RTM process.

Trials on a flat plate tool with linear sensors for flow front tracking were used to validate the filling simulation. The filling simulation shows high correlation to the flow front movement in the experiments and indicates that the calculated permeability values were correct. The relative error between the flow front movement in the simulations and experiments was always lower than 15 % and for very homogenous materials even lower than 5 %. It was shown that the homogeneity of the textile plays an important role for the permeability variation and for the accuracy of simulations.

A complex prototype tool (PT) with geometrical features and sensors was developed to validate the simulation software. Capacitive sensors are used to recognize the flow front arrival. For the measurement of the injection pressure, sensors are placed on the opposite side of the inlets. Eight temperature sensors are placed on reference points as a control for an isothermal temperature distribution. In the PT five different injection geometries can be set by inlet modules, prior to the experiment. Thus it is possible to investigate the influence of the injection scenario to the RTM process.

To preform the dry textiles they were clamped in a picture frame and heated via infra-red light to melt the powder binder on the material. The heated textiles were positioned concentrically over a preform tool and formed by a press. After forming the near-net-shape of the PT the textiles are fixed by the cured powder binder. Due to the automatic preforming step the reproducibility of preforming is very high and as a consequence the flow movements of equal RTM experiments is very similar.

Due to tension during preforming the fibers are compacted at the inner edge radii, so that there are no fibers in the outer edge radii. At these regions the permeability is much higher and builds up a runner for the resin. The runner at edge radii has to be considered in filling simulations. Preliminary testing showed that radii less than 5 mm have an influence on the flow in the RTM tool.

Filling simulations for different inlet geometries were performed and compared to experiments. For each inlet scenario three experiments with different filling conditions were carried out. One experiment where the mold was completely filled and two short-shot experiments with 2/3 filling and 1/3 filling were performed. Resin was injected with a constant flow rate until a maximum pressure of 10 bar was reached. From that point on a constant injection pressure was maintained. The experiments showed huge difference in the pressure increase, measured with the pressure sensor towards the inlet. It could be shown, that the filling with the line injection strategy is much faster due to injection time, compared to a point inlet and the risk of fiber-wash-out is lower for a slower pressure increase.

To further characterize the line injection, different shaped line injections geometries were investigated. It was found that the length of the line injection has a high impact on the filling time of the parts. However, the cross section of the line injection geometry has no significant influence on the filling time.

The sensor data of the capacitive sensors was used to compare the flow front arrival at reference points. The results showed that the experiments among themselves have a very high reproducibility for the same inlet geometry. That means the flow fronts arrival at the same reference points for the same process parameters is at the same time. The high reproducibility proves that the automated preforming process produces reliable preforms.

The comparison between the simulations and experiments pointed out that the flow front movement can be predicted very well by the filling simulation. The deviations on the reference points were partially under 15 %. That, shows that the permeability characterization of the textiles and the viscosity characterization of the resins were very accurate. The validation of the filling simulation software was therefore successful and the software can now be used as a support during tool construction or process development.

The prediction of the flow behavior of resin during an RTM process is very difficult, due to the high number of influences on the process. Nevertheless, the results of this work show that a prediction of the RTM process is possible. But to reach a sufficient level of accuracy, textile draping has to be considered. Also a process orientated material characterization of the textile permeability and the resin viscosity is necessary for accurate simulation results. Due to the reliability of the simulation it is possible to optimize the process or to support the tool design at a very early stage of automotive part development.