Kurzfassung

Für individuelle und nachhaltige Mobilität ist Leichtbau unverzichtbar. Die effiziente Ressourcennutzung ist dafür eine technische Notwendigkeit. Das Gewicht eines Fahrzeugs beeinflusst die Auslegung von Antriebsleistung, Speicherkapazität und Strukturintegrität. Kohlenstofffaserverstärkte Kunststoffe ermöglichen über die Kombination von gewichtsbezogen hoher Festigkeit eine Gewichtsreduktion. Durch das Resin Transfer Molding Verfahren können entsprechende Komponenten in hoher Stückzahl hergestellt werden. Zur weiteren Verbreitung des Werkstoffs ist eine Reduktion der Herstellkosten notwendig. In dieser Arbeit werden zu diesem Zweck werkzeugseitige Fließkanäle untersucht. Diese verkürzen den Fließweg, den das Fluid durch die niedrigpermeable Verstärkungsstruktur fließen muss. Zur Charakterisierung der Auswirkung von Fließkanälen auf den Fließfrontverlauf und die Injektionszeit wird ein Versuchswerkzeug mit transparenten Werkzeughälften verwendet. Dadurch können Fließfrontverläufe quantitativ mit einer Auflösung von einem Zeitwert pro 0,14 mm^2 miteinander verglichen werden. Eine parabolische Querschnittsform ist hinsichtlich dem Verhältnis von Ersatzpermeabilität und Querschnittsflächengröße optimal. Eine kontinuierliche Vergrößerung der Fließkanalquerschnittsgröße wirkt sich degressiv auf die Injektionszeit aus. Dadurch kann der Zusammenhang zwischen Fließkanalquerschnittsgröße und Permeabilität der Verstärkungsstruktur quantifiziert werden. Die Untersuchungen zeigen, dass die Reduktion des Fließwegs mit Hilfe von Fließkanälen auch die Auswirkung von Falten in der Verstärkungsstruktur auf den Fließfrontverlauf minimiert. Bei der Untersuchung verschiedener, möglicher Einflussparameter auf die Fasereinschwemmung in Fließkanäle werden die Fließkanalquerschnittsgröße, Durchströmung und die relative Lagenorientierung identifiziert. Durch die Verwendung von kleinen, schmalen Fließkanalquerschnitten (Fließkanalbreite < 1,5 mm) kann eine Ondulation der Fasern vermieden werden. Durch die kleinen Fließkanalquerschnitte kann die Erhöhung des Bauteilgewichts minimiert werden. Die Versuchsergebnisse werden in Richtlinien zur Auslegung der Fließkanalquerschnittsform und –größe zusammengefasst. Abschließend werden die ermittelten Wirkzusammenhänge anhand eines Beispielbauteils, Stirnwand einer Karosseriestruktur, validiert.

Abstract

Lightweight structures are essential for individual and sustainable mobility. The vehicle's weight is an important factor to dimension the driving power, battery capacity and structural integrity. Therefore the efficient utilization of resources is necessary. Carbon fiber reinforced plastics (CFRP) enable a weight reduction due to their excellent anisotropic strength. Through Resin Transfer Molding (RTM) process CFRP car components can be produced in quantity. Nonetheless for a further dissemination it is required to strengthen the economic competitiveness of CFRP. Therefore flow channels on the tool surface were investigated to reduce the longest flow length the fluid has to flow through the textile reinforcement. In general, flow channels enable a faster injection and a reduction of the required injection pressure. Furthermore, they also support the fluid distribution in the mold.

Different flow channel cross section shapes have been evaluated to characterize the influence on the flow front progression and injection time. It was shown that a parabolic cross section geometry is the optimal shape in regard to the ratio of cross section size and permeability of the flow channel. The area of effect of a flow channel was separated into an area orthogonal to the direction of the flow channel and the flow front progression in direction of the flow channel. The relevance of each area depends on the part geometry, the course of the flow channel and the orientation of the permeability tensor. The effect of flow channels on the flow front progression in the RTM process was evaluated with a transparent mold. The injection was characterized with 1.4 E07 individual local time stamps through sequential evaluation of the flow front progression. One timestamp represented the fill time of its position in the mold. This corresponds to a resolution of one timestamp per 0.14 mm^2. The influence of the flow channel cross section was experimentally investigated in three consecutive steps. The substitute permeability of the cross sections were: 4.2 E-08 m^2, 5.1 E-07 m^2 and 1.5 E-06 m^2. The corresponding filling simulation confirmed that an increasing flow channel cross section has a diminishing influence on the overall injection time. In the next step the relation between the orientation of the permeability tensor and the flow channel area of effect was shown. The optimal orientation between them depends on the intended course of the flow path. The flow path should be parallel to the direction with the highest permeability to minimize the injection time.

The simulation was extended to investigate the diminishing relation between the permeability of the textile reinforcement and the flow channel section size. In the first step, the flow channel cross section was varied in a range from E-10 m^2 to E-07 m^2. The results showed that the fluid distribution slows down over the length of the flow channel for smaller cross sections. This could result in a V-shaped flow front between parallel flow channels, which helps to avoid air entrapments between them. The same effect occurred with an increasing flow channel length. In addition, the influence of different permeability values has been assessed. For these simulations, an isotropic in-plane permeability tensor was assumed. In summary, the optimal cross section depends on the permeability of the textile reinforcement. An equation, which describes the ratio between the permeability of the reinforcement structure and the flow channel cross section, has been derived for the given arrangement through logarithmic regression.

In regards to the process robustness, a suitable configuration of the reinforcement structure and a realistic defect was evaluated in preliminary tests. The defect, a fold in a layer, was modeled with either two or three stripes of reinforcement structure. Furthermore, the orientation of the stripes and the overlapping length of the flow channels was varied. The prepared textile reinforcement was evaluated with laser triangulation, to create a height profile map of the flat dry textile. Excluding the location and intensity of the artificial fold the measurement results showed linear fiber densifications in the 45° layers. However, the effect on the flow front has been minor though.

The affected area was visualized for the experiments with an artificial fold. A fold does not only effected the area directly next to it, but moreover the area in flow direction after it. The cone shaped area was influenced by the intensity and relative orientation to the flow front of the fold. However the effect of the fold was minimized with the flow channel distribution system. The flow channels shortened the flow path to the fold and the flow path after the fold. While the injection time increased by up to 44% for the worst fold configuration with short flow channels, the same fold configuration only led to an increase of 5% for long flow channels. The same effect was observed for the standard deviation. The comparison of upper and lower tool half showed that the fluid progressed faster in the flow channel than through the adjacent textile reinforcement.

The impregnation time difference and corresponding area increased over the flow channel length.

Experimental investigations on real parts have shown that flow channels can affect the structure of the textile reinforcement underneath them, where the fibers can be drawn into the flow channel. Increased roving cross sections are characteristic for this effect. The influencing factors were characterized in a RTM experiment and evaluated with micrographs and static tensile and compression tests. Specimens with small flow channel cross sections reached one hundred percent of the reference tensile strength. However, wider cross section shapes led to a significant fiber inwash. This inwash of fibers into the flow channel caused an undulation of load carrying fibers leading to a three-dimensional stress field in the area. The tensile strength was reduced by up to 70% depending on the undulation. The presented experiments showed that apart from the cross-sectional area, the position along the flow channel and the relative fiber orientation to the flow channel can have an influence on the fiber inwash into the flow channel. The flow channel itself though, did not have a negative impact on the tensile and compression strength.

The results were summarized in design guidelines. These design guidelines have been evaluated with an existing RTM tool. This RTM tool is used to manufacture bulk heads for the car body structure. The filling simulation for the part has shown that the desired filling behavior can be achieved. The early filling behavior, which has been observed with short shots (parts were the mold is not completely filled), confirms the guidelines. Race tracking was observed in radial areas in the mold leading to air entrapments in the final part. Therefore, the local permeability distribution after the draping process has to be considered for an effective flow channel arrangement. The design guidelines support the flow channel dimensioning for the corresponding permeability of the textile reinforcement. In conclusion flow channels are an effective and necessary element of RTM tools to reduce the injection time, to guide the flow front progression through the mold and to achieve a robust filling behavior.