Kurzfassung

Bei den Flüssigimprägnierverfahren wird ein trockenes Textil mit einem Harzsystem imprägniert, wodurch Faser-Kunststoff-Verbunde hergestellt werden. Bei der Betrachtung von üblichen Faser-Kunststoff-Verbund-Bauteilen wie z. B. Motorhauben an Kraftfahrzeugen, Verkleidungsstrukturen für die Luft- und Raumfahrt oder Sportgeräte wie Ski wird deutlich, dass es sich meist um „schalenförmige“ Bauteile handelt. Hierdurch wird klar, dass bei einer Imprägnierung in transversaler Richtung, also senkrecht zur Bauteil- bzw. Textilebene, der Fließweg deutlich kürzer ist als in der Bauteilebene. Somit birgt eine transversale Imprägnierung ein großes Potenzial zur Fließweg- und somit zu einer Zykluszeitreduktion. Um das volle Potenzial bei einer Imprägnierung in transversaler Richtung nutzen zu können, müssen die Textileigenschaften für eine akkurate Prozessauslegung so genau wie möglich bekannt sein. Hierzu gehören die Faservolumengehaltsabhängige Tränkbarkeit (Dickenpermeabilität), der Kapillardruck sowie die Kompaktierungseigenschaften von Textilien. Um diese Eigenschaften zu ermitteln, wurden im Zuge dieser Arbeit mehrere Bestimmungsmethoden entwickelt, realisiert und validiert. Kern dieser Bestimmungsmethoden ist ein System welches neben dem Sättigungsvorgang, die Dickenpermeabilität sowie die strömungsinduzierte Textildeformation aufzeichnen kann. Ersteres durch die Verfolgung des Fließfrontfortschritts und Letzteres durch Verfolgung der Gesamtdickenänderung des zu messenden Textilstapels als auch der Änderung der Position einer einzelnen Lage im Textilstapel. Zur Berechnung der Dickenpermeabilität werden zusätzlich noch Druck- und Volumenstrommessungen durchgeführt. Um die Validität von ungesättigten Permeabilitätsmessungen nachzuweisen, wurde ein Kapillardruckmesssystem für eine reine transversale Strömung entwickelt. Hier wird die Fließfront in Abhängigkeit der Zeit dazu genutzt um den Kapillardruck zu bestimmen. Alle Methoden und Verfahren ermöglichen ein tieferes Verständnis der Vorgänge bei einer transversalen Imprägnierung von Textilien. Die gewonnenen Daten können zusätzlich als Eingangsparameter für Prozesssimulationen genutzt werden. Die Grundlagen einer solchen Simulation wurden erfasst und erste Simulationen zur Ermittlung einer Umsetzbarkeit bei der ungesättigten Dickenpermeabilität sowie der hydrodynamischen Kompaktierung durchgeführt.

Abstract

In Liquid Composite Molding processes, a dry fiber structure is impregnated with a resin system to produce fiber reinforced polymer composites. Common fiber reinforced polymer composites parts such as hoods for cars, aircraft cladding parts, aerospace solid fuel engine housings or sports equipment such as skis are mostly shell-like parts. As a result, the flow length in out-of-plane direction is for typical composite parts significantly shorter than in in-plane direction. Thus, out-of-plane impregnation offers great potential to reduce the flow length during the production and thus to reduce cycle times. In order to utilize the full potential of out-of-plane impregnation, the textile properties must be known as precisely as possible for accurate process design. These include fiber volume content (FVC) dependent out-of-plane permeability, textile compaction properties, inhomogeneous FVC distribution in out-of-plane direction and out-of-plane capillary pressure. The inhomogeneous FVC distribution is the results of pressure reduction during flow through the textile stack, where the pressure is reduced from injection pressure at the inlet side of the fiber stack to in usual case atmospheric pressure at the outlet side. In order to determine these properties, several measuring systems have been developed, built-up and validated. The core of these measuring systems is a system that can record not only the saturated but also the realistic unsaturated out-of-plane permeability and the flow-induced textile deformation. This includes the total thickness change of the textile stack as well as the change of position of a single layer in the textile stack. The pressure difference in the fiber stack is determined with two pressure sensors, one at the inlet and at the outlet of the measurement system. The volume flow is generated with a pressure vessel and the volume flow is tracked with a flowmeter. A spring-loaded perforated plate acts as the distribution media and follows the compaction of the measured fiber stack together with three spring-loaded displacement sensors, enabling tracking of the movement of the perforated plate. With this method, the change in the thickness of the fiber stack can be monitored. Ultrasonic sensors are used to track the position of an insert placed within the fiber stack. The insert is a piece of aluminum foil with a diameter of 10 mm and a thickness of 10 µm, which reflects the ultrasonic signal. When the position of the insert changes, the time-of-flight of the sound signal changes, which can be used to determine the change in position. With this information, the change in the position of the insert and thus the position of the following textile layer can be tracked and this can be used to estimate the inhomogeneous FVC distribution in out-of-plane direction. An ultrasonic sensor is also used to monitor the flow front progression depending on time as basis for unsaturated out-of-plane permeability calculation. Therefore, the change of the sound signal velocity due to the saturation process is used.

To evaluate the influence of the out-of-plane capillary pressure, a capillary pressure measurement system for a pure out-of-plane flow was developed. This system is further necessary to prove the validity of unsaturated out-of-plane permeability measurements. This measurement system determines the flow front progression depending on time by using a scale to track the mass increase due to the capillary pressure. A novel sealing concept, which seals the fiber stack at the edge area with a two-component silicone, preventing any flow in the in-plane direction, was developed ensuring pure flow in the transverse direction. For the final calculation, a special solution of the Navier-Stokes equation is used.

During flow-induced textile deformation, the fiber stack is not compacted uniformly. The fiber stack exhibits a non-uniform FVC distribution, where a single textile layer can be compacted and relaxed serval times during impregnation. For input parameter for simulations, the average compaction behavior of a single layer of different textiles were determined. An arrangement of alternating textile layers and separation plates, made out of carbon fiber reinforced polymer, was placed in a universal testing machine and the arrangement was compacted with a defined compaction speed to a final compaction force. Using this method, the compaction behavior of a defined single textile layer cannot be determined, along with the average compaction behavior of a single layer of textile type. To ensure that the mechanical behavior of the separation plates do not have an influence on the investigation, the compaction behavior of the plates has been determined separately and this has then been considered during the evaluation of the measurements. However, nesting effects are not considered in these measurements, which in turn leads to a deviation in the results.

Results from the measurements have therefore been used to develop a finite element based simulation model, with the goal to check if simulations can be used additional to experiments. Process simulations can lead to a deeper understanding of the process and show details that are difficult or impossible to measure experimentally.

Furthermore, simulations can be used to quickly, effectively and inexpensively carry out investigations that would be much more complex with physical experiments. A detailed 3D fluid-structure-interaction model of the measurement system itself was created. The positions of the various sensors in the measuring system were also specified as measuring points in the simulation to ensure the best possible comparability.

The measurements with the out-of-plane permeability measurement system as well as the single layer compaction measurements have been performed with a glass fiber woven (2/2) and the biaxial non-crimp fabric. For the capillary pressure measurements additional a glass fiber random mat was used.

Due to the new out-of-plane measurement concept, determination of the unsaturated and saturated out-of-plane permeability with the exact same fiber stack is possible. All boundary conditions such as FVC, injection pressure, fluid viscosity etc. remain equal. Only the saturation condition of the fiber stack differs. The woven reinforcement shows a 42% to 63% increase in permeability in the unsaturated state compared to the saturated state while the non-crimp fabric a 48% to 67% better permeability compared to the saturated state. Furthermore, inhomogeneous compaction effects could be verified by single layer displacement tracking.

The capillary pressure measurements have been performed with three different FVC for each textile. Three repeat measurements were carried out for each textile. The capillary pressures ranged between 150 and 225 Pa which is in this negligibly low.

With the simulation the unsaturated out-of-plane permeability as well as the total compaction and single layer displacement of Saertex X-E-444 could be determined for three different FVC. Here, very good agreements could be demonstrated. Furthermore, the simulation was used to determine the FVC distribution of a Saertex X-E-444 with 49.3% FVC. The FVC distribution agrees with the results from the literature and is therefore plausible.

All methods and procedures described here allow a deeper understanding of the processes during the transverse impregnation of technical textiles, which in turn can lead to process improvements and thus to better economic efficiency of fiber-reinforced plastic composites by e.g. process and material optimization.