Kurzfassung

Bei Harzinjektionsverfahren wird eine trockene Faserstruktur mit einem reaktiven Harzsystem imprägniert, um einen Faser-Kunststoff-Verbund herzustellen. Dabei gewinnen Verfahren an Bedeutung bei denen die Imprägnierung hauptsächlich transversal, also senkrecht zur Bauteil- und Textilebene, stattfindet. Sie bergen im Vergleich zur Imprägnierung in der Ebene ein großes Potenzial zur Fließweg- und damit Zykluszeitreduktion. Allerdings behindern strömungsinduzierte Textildeformationen die volle Ausschöpfung dieses Potenzials. Im Rahmen der Arbeit wurde ein neues Messsystem entwickelt, welches die gezielte Untersuchung des transversalen Imprägnierverhaltens von Textilien ermöglicht. Erstmalig wurde eine Dickenpermeabilitätsmessung mit einer simultanen Echtzeiterfassung der strömungsinduzierten Textilkompaktierung kombiniert. So konnte das Textilverhalten prozessnah untersucht werden. Mit dem neuen Messsystem wurden anhand exemplarischer Textilien (Glasfasergewebe und –gelege) zahlreiche Einflüsse auf das transversale Imprägnierverhalten identifiziert. Diese ergeben sich aus dem Prozess (z. B. Injektionsdruck), der Textilarchitektur (z. B. Garntiter) und dem Preforming (z. B. Bindern).

Vor allem konnte gezeigt werden, dass eine Erhöhung des Injektionsdrucks, aufgrund von Textildeformationen, nicht zwingend zu einer Imprägnierzeitreduktion führt. Unkenntnis über das transversale Imprägnierverhalten von Textilien stellt daher ein großes Risiko für die Prozesseffizienz und –robustheit dar, denn meist werden nicht die zykluszeitoptimalen Parameter gewählt. Hingegen kann entsprechendes Know-How zur gezielten Parameterfestlegung genutzt werden. Die Parameterstudie zeigt weiterhin auf, wie das transversale Imprägnierverhalten durch Anpassung der Textilarchitektur oder gezieltes Preforming hinsichtlich einer minimalen Imprägnierzeit optimiert werden kann. Die Ergebnisse wurden in Richtlinien für die Definition von Prozess- und Materialparametern sowie für die Nutzung von Preformingtechnologie für transversale Imprägnierprozesse zusammengefasst. Abschließend wurden die entwickelten Richtlinien validiert, indem exemplarisch ein für Strukturbauteile typischer Lagenaufbau anhand der Richtlinien angepasst wurde, um ihn hinsichtlich des transversalen Imprägnierverhaltens zu optimieren.

Abstract

During Liquid Composite Molding (LCM) a fiber structure is impregnated with a resin system in order to manufacture a fiber reinforced polymer composite (FRPC). Process variants which provide transverse instead of in-plane impregnation gain in popularity, since they offer the opportunity to dramatically shorten cycle times, due to the massively shortened flow lengths. Corresponding processes, such as Advanced/Compression RTM, SCRIMP, Wet Compression Molding or Film Stacking allow the efficient manufacturing of high performance FRPC. However, during the transverse impregnation textile deformation occurs, which can strongly reduce the process efficiency. Thereby, the transverse impregnation behavior of textiles is very complex to describe and predict, due to the interdependency of textile transverse permeability and compaction behavior. The process stability and efficiency are threatened if the textile impregnation behavior and its dependence on different influences are not understood. On the other hand, knowledge about such influences offers a chance for specific manipulation of the textile impregnation behavior and improvement of process efficiency. Correspondingly, the target of the presented research was to holistically describe influences on the transverse impregnation behavior of textiles, in order to transfer them from threats into opportunities.

For this purpose a novel measurement system was developed, to realistically reproduce the process conditions during transverse impregnation. It allows an online compaction monitoring, simultaneous to a transverse permeability measurement. At first, the system was extensively tested concerning its functionality. It was proven that the measurement can be considered as non-invasive and that the application of the law of Darcy for the calculation of the transverse permeability is valid. With a reference structure and a statistical error analysis it was shown that the inherent measurement error is $< \pm 4$ %, which allows statistically profound statements.

In a next step the system was used to perform a copious study concerning the influence of process-, textile-, and preforming-related influences on the transverse impregnation behavior. As a starting point glass fiber woven fabrics and glass fiber non-crimp fabrics were chosen. Thus, two cases of main industrial relevance are covered by the study. Within the novel system the textile reaction to different transverse flow conditions in terms of compaction and resulting transverse permeability was measured.

It was found that with increasing pressure drop a severe hydrodynamic compaction of the textiles takes place. An increase of the initial fiber volume content of up to 7.5 percentage points and a corresponding transverse permeability reduction of about 80 % were measured at pressure drops below 5 bar. It was therefore shown that with increasing injection pressure the achievable increase of flow velocity stagnates. The hydrodynamic compaction can even cause a flow rate reduction with increasing injection pressure. Hence, a correct process parameter selection is of high importance for the process efficiency and increasing injection pressure does not automatically reduce the cycle time.

The results also revealed that a transverse impregnation will not only cause a compaction of the stack in total, but will also lead to a heterogenization of the fiber distribution. This heterogenziation also causes a transverse permeability reduction. Thus, even if the pre-compaction of the textile within the tool is not exceeded and therefore the total fiber volume content remains constant, an increase of the injection pressure can cause a transverse permeability reduction. Since the transverse permeability depends on the total fiber volume content, but also on the fiber structure heterogenization caused by certain flow conditions, it should be described as a function of both – fiber volume content and flow condition (e.g. pressure drop).

Further studies confirmed a viscoelastic-plastic compaction behavior of textiles. Due to plastic deformation, multiple flow cycles, with increasing and decreasing injection pressure, reduce the textile compaction resistance. A further finding is that with a fast increase of the injection pressure, the textile viscoelasticity can be utilized to cause temporarily higher flow rates.

During LCM processes a dry reinforcement gets impregnated which corresponds to an unsaturated flow. It was found that the saturated transverse permeability is higher than the unsaturated transverse permeability.

In order to investigate the influence of textile- and preforming-related parameters, samples were prepared, which only differed concerning one single parameter. Subsequently, the textile reaction to specific flow conditions was compared.

For woven fabrics it was found that an increasing number of layers, a similar orientation of stacked layers, and a smaller number of yarn crossing points is advantageous

for high flow velocities. For the non-crimp fabrics an increasing number of layers, a similar orientation of stacked layers, a higher linear yarn density, and a higher stitching length lead to higher flow velocities. Due to the pore space heterogenization the flow direction can affect the transverse permeability of mixed layups.
The preforming studies revealed that sewing technology offers various opportunities to manipulate the transverse impregnation behavior in terms of compaction and transverse permeability. For example tufted samples partially showed a transverse permeability increase of over 114 %. Thermoplastic binder on the other side reduces the transverse permeability by reduction of pore space in a range of - 35 % to - 50 %. However, it was proven that by placing unmolten binder webs between textile layers hydrodynamic compaction can be impeded at higher pressure drops. Thus, the available transverse permeability is preserved. Shearing reduces the transverse permeability by increasing the material density and geometrical changes, whereby the share of the latter is below 10 %. A maximal shearing and subsequent back-shearing to 0° increased the transverse permeability of both textiles by about 30°%. Dry precompaction cycles can be used to reduce compaction resistance and increase reproducibility of compaction behavior.
The results were summarized and transferred into guidelines for process, material, and preforming parameter selection. By identifying the basic effects causing variation of transverse impregnation behavior these guidelines can also be used to evaluate parameters not covered by the study. Finally, to validate the developed guidelines, they were exemplarily applied to a textile lay-up as it can be for example found in structural applications. At a pressure drop of about 1 bar the transverse permeability of the lay-up could by increased by 415 %.

All in all the results can support the selection of process parameters, textiles and preforming technologies for transverse impregnation processes. Also, the results are of interest for numerical simulation, since a method for detailed and process-near measurement and description of textile behavior was found.