Kurzfassung

In der vorliegenden Arbeit wird die Entwicklung und Beurteilung einer alternativen kontinuierlichen Preform-Technologie zur Vorstabilisierung von trockenen Kohlenstofffaserhalbzeugen unter Verwendung der Ultraschall-Schweiß-Technologie für Kunststoffe präsentiert. Aktuell verwendete Technologien für Großbauteile in der Luftfahrt sind in der Regel diskontinuierlich und wenig produktiv. Zudem weisen sie Probleme hinsichtlich des gewünschten Kompaktierungsgrades und der Oberflächenqualität auf. Diesen Nachteilen soll durch den Einsatz des kontinuierlichen Ultraschall-Preformens begegnet werden.

Innerhalb der Ausarbeitung wurde eine neue Funktionseinheit, die für die Anforderungen in einem kontinuierlichen Preform-Prozess geeignet ist, entwickelt und mit passender Sensorik und Steuerung in einen Versuchsstand integriert. Durch statische Versuche konnte das halbzeugabhängige Aufheizverhalten untersucht werden. Es zeigte sich, dass der Erwärmungsprozess durch Reibung zwischen den Filamenten bestimmt wird und somit einen homogenen Prozess unterstützt. Untersuchungen der Parameter führten zu diskreten und materialabhängigen Prozessfenstern und einem tieferen Verständnis für die Einflüsse des Schweiß-Prozesses auf das Preform-Verhalten. Durch die Betrachtung von Prozessgrenzen konnten unerwünschte Strukturdefekte ausgeschlossen und das Potenzial für die Nutzung verschiedener Materialien sowie für den Einsatz an komplexeren Bauteilen aufgezeigt werden. Weiterhin wurde durch Permeabilitätsuntersuchungen gezeigt, dass es einen materialabhängigen Einfluss des Prozesses auf die Infusionierbarkeit gibt, der sich sowohl als eine Verbesserung als auch eine als Verschlechterung darstellen kann. Durch vibrationsinduzierte Verdichtungsprozesse konnten höhere Faservolumengehalte bei einer gesteigerten Produktivität erzielt werden. Auch eine partielle Verbesserung der mechanischen Eigenschaften ist durch die Anwendung des Ultraschall-Prefom-Verfahrens möglich. Für die Herstellung komplexerer Strukturen eignet sich das Verfahren ebenso, wie an einem Demonstrator gezeigt werden konnte. Geometrische Restriktionen grenzen die Anwendbarkeit allerdings ein.

Durch die Entwicklung der Technologie konnte eine vielversprechende Alternative dargelegt werden, die Kosten sparen und Bauteileigenschaften verbessern kann.

Abstract

Carbon fiber reinforced polymer composites (CFRPC) have aroused increasing interests for structural and non-structural parts not even in the aerospace industry, because of their great mechanical properties related to the low specific weight. This progress can be seen observing the increasing material share of composites used in the new developed airplanes, like the A350 or the Boeing 787. Due to that fact a higher level of flexible automation to produce CFRPC-parts is claimed by the industry to save costs, material and time as well as to achieve a more reproducible quality.

One important step in the process chain using bindered dry-fiber material for manufacturing of CFRPC-parts with infusion technologies is the preforming process, which is needed to obtain a certain fiber volume content and to stabilize the dry fiber preform to a claimed geometry for further processing. Thereby a certain amount of layers will be joined using the polymer based binders in between. Within the aerospace industry the so called sequential preforming using bindered material is preferred towards stitching processes because of a lower disturbance of the fiber architecture and the possibility to reach a higher densification.

State of the art technologies used in the aerospace industry like convection ovens or IR-beams in combination with vacuum-bags are discontinuously, not time efficient, expensive, difficult to automate and the use of a vast amount of auxiliary-material is necessary. All these disadvantages make clear, that a development of an alternative process is of current interest. Ultrasonic welding was identified as an alternative cost efficient technology for joining layers. The challenge is to develop a continuous preforming process by the means of ultrasonic welding for large and complex parts following the design of aerospace structures. The idea is that a sonotrode should be moved relative to a stack of carbon fiber layers with a certain feed velocity. Thereby a specific weld pressure as well as an amplitude must be applied perpendicular to the surface to generate the necessary energy activating the binder. To meet this challenge first there is a need to develop a new function unit within a test rig. Afterwards it is possible to perform tests to understand the working mechanism as well as to evaluate the process limits and to define proper parameters to achieve the claimed material quality. Furthermore there will be an investigation on the influence of the process to the mechanical properties of the final part. Finally it is claimed to have a look onto the feasibility using this technology for more complex parts.

The new developed function unit bases on a 35 kHz oscillation unit with a special bearing to avoid problems caused by transverse forces. The core of this unit is the adaptive adjustment system to ensure a proper alignment of sonotrode and material surface. Additionally several sensors to monitor the process were implemented. This unit was integrated into a stiff test rig with a linear feeding axis for material transport. A proprietary control system was established to realize automated manufacturing cycles and to record all process data for evaluation.

To ensure the process quality an assurance system by the means of an IR-camera was integrated. To validate the measurement on the surface investigations on the temperature development within the laminate were performend. The results have shown that the heat mechanism mainly bases on inter-filament friction due to the ultrasonic vibrations. This leads to a homogeneous heat distribution all through the material and to a characteristic temperature profile on the surface, which can be used to evaluate the process and to detect fiber miss-alignments.

Investigations to point out the process limits and disturbance values have shown that the weld pressure as well as the inclination of the sonotrode to the material surface has a huge influence on the process quality. Therefore it is necessary to adjust the parameters to avoid unsufficient quality. Observations regarding the maximum numbers of layers could be joined have illustrated that the damping effect with increasing material thickness has no significant influence to the process. Therefore parts with a thickness of more than 20 mm can be realized without issues. Further investigations confirmed the possibility to use multiple sonotrode arrays to preform large parts with a certain overlapping area without an over-compaction. Not even using arrays a homogeneous thickness all over the specimens could be observed. Geometrical restrictions have to be mentioned as an disadvantage using this technology, due to the fact that an flat contact between sonotrode and material surface must be ensured. Beside carbon fibers it is also possible to use glass fabrics as well without documented issues.

Influence and parameter studies have shown that it is possible to identify a certain process window related to each material to achieve a relative fiber volume content between 60 % and 65 %. In general a high amplitude (in this case of 23.1 µm) and a low weld pressure between 0.1 MPa and 0.15 MPa are recommended. The value to control the process individually was set to the feed velocity. Depending on the material this value differs between 10 mm/s and 25 mm/s. Static comparisons to conventional technologies (vaccum or heat press) have shown the potential even for continuous processing. It is possible to reduce the heat time by more than 2000 % and to increase the fiber volume content to values of more than 70 %. Due to the increasing compaction and different binder distribution a permeability study was performed. Of course, an increasing compaction leads to a pure permeability. However, because of the short heating time the flow channels in fabrics for example remain open, which leads to an increasing permeability. Therefore the impregnation behavior is influenced, but the occurring effect depends on the selected material.

The influence of the ultrasonic compaction process on the mechanical properties (Tension, ILSS, CAI) was investigated as well by a comparison to conventional manufactured specimens by the means of vacuum compaction. The infusion was done by RTM and VAP-Processes. The main proposition is that there is no degradation in the results for any specimen. Regarding the VAP-Process even partly increasing values could be observed for the ultrasonic specimens. Depending on the material the shear strength increases due to a better layer connection as well as the Young's Modulus for fabrics. This is because of the decreasing undulations effected by the higher compaction rate and the better fiber alignment. The results of the CAI-Trials have shown smaller damage areas and partly increasing compaction strength. This can lead to improved dimensioning possibilities.

A feasibility study has shown that it is possible to use this technology for more complex parts as well. Using special formed sonotrodes it is possible to manufacture also parts with continuous shapes. Beside a qualitatively improvement the feasibility test has presented a huge time saving potential. For the chosen part a lead time reduction of more than 50 % is possible.

Summarized in the present work a new pre-stabilization process for dry fiber material could be presented. As well for an increasing productivity and a higher degree of automation as for improved part properties this technology shows a promising alternative to conventional technologies.