Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 18 (2018) 35–42

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

18th Machining Innovations Conference for Aerospace Industry, MIC 2018

Flexible and automated production of sandwich panels for aircraft interior

Henrik Eschen[a]*, Martin Harnisch[a], Thorsten Schüppstuhl[a]

[a]*Hamburg University of Technology, Institute for Aircraft Production Technology, Denickestr. 17, 21075 Hamburg, Germany*

Abstract

The demand for aircraft interior equipment is constantly growing due to general increase of personal air travel, individualization of design and limited life cycles. This especially poses challenges to the manufacturing of sandwich panels as a main component of interior parts. The current processes need to adapt to the increasing demand for individualized parts in small batches. In this paper, we propose a concept for the automated production of planar sandwich panels consisting of NOMEX honeycomb core and fiber reinforced prepreg sheets. The concept consists of an optimized process chain, concepts for automated honeycomb potting and automated sandwich laying. A novel approach for modelling of the potting process is developed to ensure completely filled cells without air entrapment. Simulations and time analysis show the general feasibility and give a first estimation of achievable production rates. The conclusion of the paper outlines the focus of further research.

Peer-review under responsibility of the scientific committee of the 18th Machining Innovations Conference for Aerospace Industry.

Keywords: Automation; Manufacturing; Aircraft Interior; Honeycomb; Sandwich Structures

1. Introduction

The air travel market benefits from a continuous growth that seems to be robust against global crises as shown in the recent market analysis from Airbus [1]. Historical data shows a doubling in air traffic every 15 years and until 2036, a global annual air travel growth of 4.4% is predicted. The resulting high demand for new airplanes paired with long lifecycles of about 20 years generates revenue potentials for OEM and aftermarket suppliers. In this sector, the cabin interior is of special interest, with partial replacements in up to yearly intervals and complete refurbishments up to every eight years [2]. The interior is made mostly of composite sandwich structures, often produced in manual labor

---

* Corresponding author. Tel.: +49-40-42878-2504; fax: +49-40-42878-2500.
E-mail address: henrik.eschen@tu-harburg.de

2351-9789
Peer-review under responsibility of the scientific committee of the 18th Machining Innovations Conference for Aerospace Industry.
10.1016/j.promfg.2018.11.005

[3]. Automated processes are necessary to satisfy the growing demand and the competitiveness to low-wages-countries. Automation could cut production costs not only by reducing the manual labor hours, but also by reducing material scrap rates and increased quality and repeatability [4]. Production in small batches due to frequent design changes and individualized adaptions as well as the complex material behavior of sandwich materials are critical challenges. Available literature exists only in form of handbooks, explaining the materials and general manufacturing processes [5,6]. The following sections give an overview of related work and general requirements for automation.

2. Background

2.1. Material limitations

Even though the use of FRP for structural parts is very present in scientific discussion, sandwich panels used in interior make up the major part of the composite materials in airplane production [2]. The basic construction materials are phenolic resin preimpregnated woven fiberglass layers (prepreg) for face sheets and honeycomb structures out of aramid paper (commonly referred to as Nomex, a trademark from DuPont) as core layer. Potting compound, monolithic structures made out of cotton fabric and phenolic resin as well as metallic inserts between core and face sheets are regularly used to locally improve stiffness and compressive strength. The materials pose the main obstacles to automation: the variety is limited due to cumbersome certification processes whereas complex behavior of available materials such as rigidity, anisotropy and hydrophilicity complicate handling.

2.2. Automated production of sandwich panels

Work related to automated production of sandwich panels for aviation focuses on pure fiber composites for structural and external parts (e.g. [4,7–9]). One major topic is the layup of prepregs with varying tackiness and dimensions on complex tool surfaces. Much work has been done on pick & place operations of prepreg. The most common solution are low-vacuum grippers, as used by Björnsson et al [9]. Needle grippers are often used in textile handling and also applicable to some fiber composites like preforms [11], but could potentially break and remain in the prepreg [9]. In preliminary tests, this technology has shown its potential on gripping of the honeycomb core. Szcesny et al [12] have used clamping grippers to lay multiple strips of unidirectional prepreg in 3D tools. These grippers have two main restrictions: gripping points need to be on the edges of the layers and the edges need to be accessible from both sides.

Automated honeycomb potting currently receives much attention in aircraft production industry, and suppliers like Airborne are already promoting standalone systems but no research work regarding this technology is known.

While some of the proposed technologies can be used or adapted for honeycomb sandwich production, integrated solutions for automated manufacturing of complete sandwich panels for aircraft interior are needed. The handling of the core, the integration of additional materials for local stiffening as well as the integration in the overall process chain introduce new technical obstacles not solved by current research works.

Proposals for integrated production of honeycomb sandwiches come from other industrial branches, such as packaging and furniture. Pflug et al [10] present two continuously produced sandwich materials: TorHex is made of cut and folded corrugated cardboard, ThermHex uses thermoformed and folded thermoplastic films. Using certified polycarbonates the ThermHex could be an economic alternative for less demanding parts (e.g. casings), as demonstrated in an industrial project of EconCore and Diehl Aircabin. The lower strength of the mono-material thermoplastic honeycomb sandwich panels still restricts the widespread replacement of classical aramid honeycomb.

2.3. Technical requirements and limitations

The honeycomb sheets mainly used in aircraft interior have a standardized size of 1120 ±50 x 2440 ±75 mm and thicknesses between 10 and 40 mm [13]. Nesting of multiple smaller parts in one sandwich panel is possible for maximizing material utilization. Prepregs are commonly supplied on rolls with a width of 1270 ±15 mm with separating backing paper, for automation one-sided protection should be preferred. Since this work focuses on flat panels, material with low tackiness is used [14]. The panels can be reinforced locally either by potting material or by prepreg strengtheners of varying shape. Their size is usually between 70 x 70 and 1270 x 500 mm. To enable component transfer, the different sandwich layers are typically placed upon flat aluminum workpiece carriers during the laying process. Fig. 1 illustrates the total layer structure during production. The prepregs are usually co-cured with the core in flat hot presses. To achieve a small footprint multiple independent hot presses can be arranged vertically in a common frame. Automated transfer and storage systems are available for storing of the workpiece carriers with the prepared and finished panels as well as to compensate cycle times in the laying process. Multi-axis CNC-milling machines are used for machining.

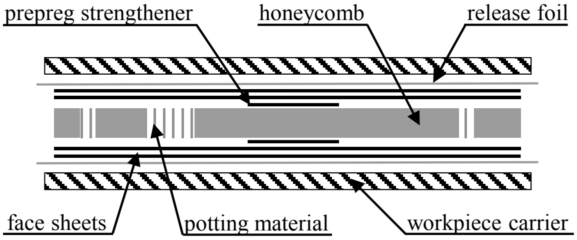

Fig. 1: sandwich panel structure

3. Concept for automated production of sandwich panels

3.1. Optimized process chain

Due to the high variance in production processes, process standardization is needed in order to enable efficient automation. Therefore, the production processes of flat sandwich panels have been analyzed. Afterwards a minimal subset of processes has been selected with regard to process standardization and automation capacity in order to standardize the process chain. The optimized process chain is shown in Fig. 2a.

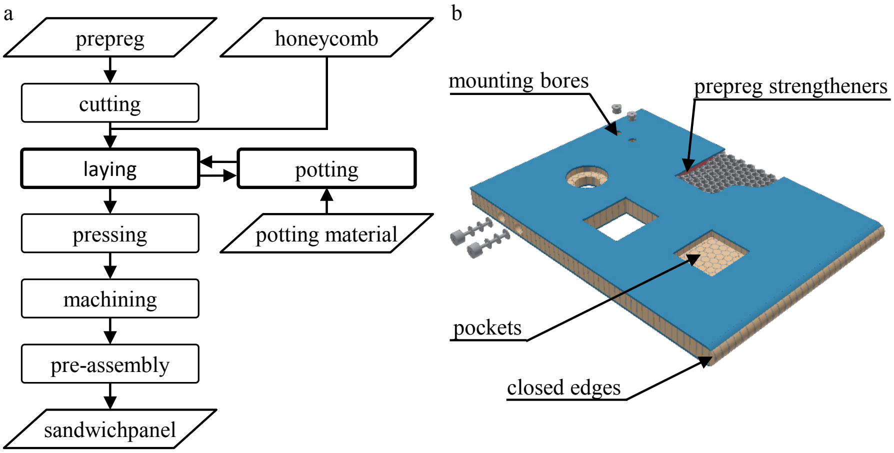

Fig. 2: (a) optimized process chain; (b) example for optimized panel design

It was found that all identified feature groups can be manufactured with a combination of automated potting, automated laying of face sheets and prepreg strengtheners as well as curing and machining. The manufacturing of e.g. strengthened core areas, closed edges and closed pockets is possible with a combination of potting, curing and milling (Fig. 2b). Additional components (e.g. inserts) are mounted after machining during pre-assembly.

3.2. Preliminary tests

For a more accurate characterization of the material properties, the adhesive forces between the different materials have been measured. It has been found that the adhesive forces vary greatly with changing environmental conditions like humidity and temperature. Adhesive forces of the prepregs increase greatly, if moisture ingression occurs during defrost. The adhesive forces in normal direction between backing paper and prepreg are usually very low, hence it is not possible to grip the Prepregs at the backing paper like proposed in [15]. At the same time, the removal of the backing paper can be problematic in case of moisture ingression. The adhesive forces in lateral direction between prepreg and release film are usually low as well, therefore insertion of high lateral forces should be avoided during the laying process. Between release film and workpiece carrier almost no lateral forces can be transferred. To ensure a robust process a fixing system for the release film is needed.

3.3. Plant concept

Based on the optimized process chain a plant concept for automated production of flat sandwich panels has been developed. All necessary components have been identified, variants for each component have been discussed and multiple fundamental plant layouts have been developed. Resulting from a first estimate of costs and cycle times the variant described below was chosen. Due to relatively low costs, high versatility and a big workspace compared to the footprint, a standard six-axis industrial robot should be used for the layup, the potting process as well as the handling of the finished panels. Based on an analysis of size and weight of the handled components and grippers, a robot with a handling capacity of 90 kg and a reach of 3.9 m was chosen. To prevent the Prepregs from sticking to the workpiece carrier during curing, release foil or release wax can be used. Since a cleaning process is necessary when using release wax, release foils are better suited for automation.

For the layup process of the prepreg and the release foil, two basic variants were considered. The first variant is to cut all materials with one automated cutter in advance, transfer the cut pieces to the robot cell and store them in single layers in a storage system. The second variant is to store the materials inside the cell on rolls and cut them right before use. Due to simpler and more space efficient storage, less material transfer as well as no need for referencing of the cut parts the second variant was chosen. Since the face sheets and the release foil only need to be cut to length and differ in size from the individually shaped prepreg strengtheners, face sheets and strengtheners are considered separately. A paternoster storage with an integrated linear cutting system is used for storing, changing and cutting the release foil as well as different types of prepreg during layup. Similar to the functional principle of Automated Tape Laying-Heads [16] the backing paper can be separated and wound up on an additional roll during unwinding of the prepreg. For cutting of the prepreg strengtheners, the usage of a standard automated cutter as well as a separate cutting table with integrated prepreg storage, backing paper removal and a robot mounted cutting tool are suitable. Based on the estimate of costs and cycle times the second variant is used. For handling of individually shaped prepreg elements, usually matrix grippers with individually controlled suction cups are used. To avoid contamination of the inactive suction cups with potting material the suction cups need to be retractable. A Concept for such a gripper is shown in (Fig. 3a).

For a bubble and wrinkle free layup of the prepreg layers as well as the release foil the robot is supported by an additional linear axis with a separate vacuum gripper. The laying principle for the prepreg layers and the release film is shown in Fig. 3b. First, the robot will grip the edge of the material with one row of suction cups of the matrix gripper and unwind the material by pulling it over the workpiece carrier (1). Second, the linear support axis will grip the material near the cutting position (2). Third, the material will be cut by the linear cutting system (3). Fourth, the horizontal support plate is turned in a vertical position and the support axis places the first edge of the material on the workpiece carrier (4). Last, the robot places the material with a curved movement on the workpiece carrier (5). For fixation of the release film on the workpiece carrier, vacuum will be drawn through small holes at the edges of the workpiece carrier. For core filler dispensing multiple solutions are available. First consideration is the packaging volume. The common and therefore economic packaging are 20-Liter drums. The drums are emptied with hobbocks, and the material is metered with volumetric pumps close to the dispensing nozzle. Common solutions include gear pumps and progressive cavity pumps. While gear pumps lead to smaller tool dimensions, they introduce higher shear forces to the potting material, which could potentially damage the additives (glass microspheres). Since no reliable data is available for material deterioration the progressive cavity pumps should be preferred. The dispending nozzle is moved along the surface of the open core, preliminary tests showed good results for diameters of 10-25mm.

The honeycomb panels as well as the finished panels can be space efficiently stored and transferred in stacks on moveable trollies. To reduce the total number of grippers, the matrix gripper will be used for gripping of the finished panels. Needle grippers can be used for gripping the honeycomb panels. Multiple grippers need to be distributed over the size of the panel in order to prevent sagging. Due to the high tolerances of the honeycomb sheets, position and orientation needs be measured during placement. For this purpose, two laser distance sensors per side will be used. For referencing, two sticky markers will be placed on the finished panel using a robot mounted labeling tool. The marker positions will be measured relatively to the workpiece carrier with a calibrated camera system and image processing. Accuracies can be improved by using separate cameras for each marker. For quality assurance, the thickness of the finished panels is measured at different positions. Therefore, the robot will position the panel multiple times between two pneumatically actuated inductive displacement sensors.

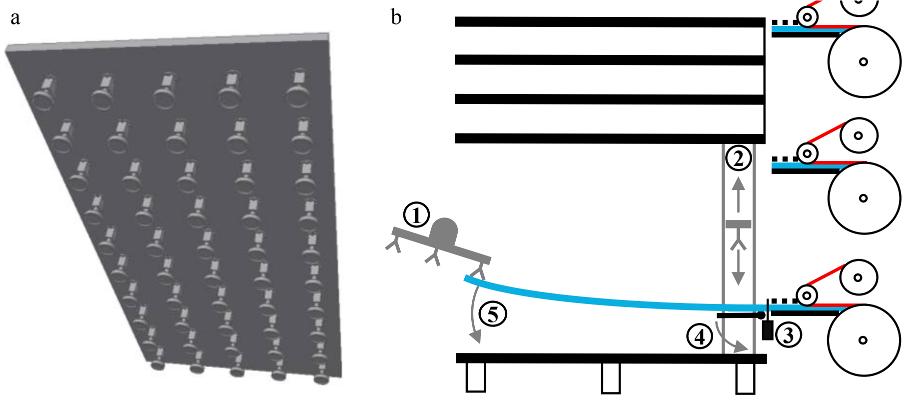

Fig. 3: (a) concept of matrix gripper; (b) concept for laying process

3.4. Potting model

The potting process seems trivial at first glance and no research work is known on this topic, but industrial insight shows that the material behavior of the potting material and interaction with the core, underlying prepreg sheets and other environmental influences lead to complex interrelations that are not yet fully understood and controlled. Main issues of faulty setups are entrapped air and potting spillage (e.g. smearing). As with the layup of FRP sandwiches [6], it can be expected that the automation industry lacks the material or process knowledge

Possible solutions for honeycomb potting that could potentially circumvent the issues of air entrapment and spilling are individual filling of the cells with needle arrays or filling of the completely open core in a separated production step. From these concepts, different problems such as lower productivity, difficult control and cumbersome integration in the overall production would arise. In the proposed process of dispensing through a nozzle with an area larger than a singular cell during the sandwich layup, the spilling can be prevented with correct values for flow rate and tool velocity as well as precise positioning of the nozzle over the core layer. The latter is achieved via an auxiliary actuator included in the tool. Process parameters are dependent from the overall setup and material composition. Available industrial solutions generate these settings with trial and error without deeper knowledge of the underlying phenomena. This procedure is valid if the material is only dispensed in single, not overlapping paths. As larger areas are filled where the paths must overlap in varying percentages, the changing conditions prevent repeatable results.

Research at the IFPT focuses this problem by developing a process model that can be embedded in the dispensing control. As soon as potting material enters a cell, the air can only evacuate at the interface between prepreg and core or through the prepreg. The Law of Darcy generally describes liquid flow in porous materials and taking into account the anisotropic behavior, it is applicable to airflow in prepreg. The porosity values for in-plane and through-plane flow differ by two magnitudes, which can lead to deviation from simple 1D pressure gradients. Kratz et al [17] proposed the use of a lower effective permeability, calculated from CFD simulation results. Still, permeability values need to be determined experimentally. Once obtained, these can be used as input for offline path planning and potting simulation, which itself is a valuable asset during the conceptualization and design phase of the process and its tools. Specifically, it should be used to optimize dispensing parameters, nozzle geometries and tool velocity. The first two are determined only once for a given setup and depend on technical requirements, such as used material, potting area dimensions and the dispensing system. With the tool dimension, the path planning subdivides the defined potting areas into single, machine-processable paths. These are fed to the potting simulation, which optimizes velocities for each part segment by calculating the aforementioned process conditions.

4. Simulation of automated production chain

For detailed cell design, time analysis, accessibility analysis and collision detection the proposed plant concept has been simulated. A simulation model including the robot, the robot tools, the storages, the cutting table as well as the honeycomb sheets has been implemented in the simulation software ABB Robot Studio. The simulation model is shown in Fig. 4. Safety equipment (e.g. fence) is not part of the simulation model.

In order to get accurate simulation results detailed descriptions of the manufactured components where needed. Especially the average number of face sheets, the average number and size of prepreg strengtheners, and the average volume of potting material had to be known. Since the proposed optimized process chain has not yet been implemented and changes to component design are needed, current design data could not be used. Three different scenarios for future component design have been developed based on the analysis of an existing lavatory assembly and the results of the process analysis. Based on the scenarios, weighted averages for the number of face sheets, the number of strengtheners and the amount of potting material per panel have been calculated. With these data, a generic sandwich panel has been designed and all needed robot paths and tool changes for the laying and cutting process have been programmed. Afterwards the individual times for the different steps of the laying process where gathered. Since the velocity of the robot tool during dispensing of the potting material is limited by the maximum volume flow, only the tool changes as well as the approach movements where simulated for this process step. The remaining time for the potting process was calculated with the total potting volume inside the panel and the achievable volume flow. The times for the inter tasks are negligible since the tool velocity is high and the distances are short compared to the dispensing movements. The total time needed for layup and potting is ~20 minutes per panel. An overview of the time distribution of the different process steps is shown in Tab. 1.

Based on the simulation 72 panels can be prepared per day. The number of panels per day that can be cured in one press is limited by the material dependent curing time. Taking typical curing times for prepreg and potting material into account, a press tower with four independent hot presses could be fully utilized. This would result in 82% actual machine utilization of the robot system, which leaves enough time for daily material change as well as maintenance.

To discuss the profitability, the total cost for the proposed plant, including costs for parts, engineering and programming have been estimated. Taking the uncertainty involved in those cost estimations into account a payback time between two and three years can be expected due to reduced labor costs as well as reduced material scrap rates compared with a manual laying and potting process. Further potentials for cost reduction, timesaving and quality improvement during the design process, production planning, panel production as well as pre- and final assembly would be provided by an adaption of the component design due to process and design standardization, tighter tolerances, less manual rework and higher levels of prefabrication. Therefore, an optimization of component design as well as a more detailed analysis of costs and savings is needed.

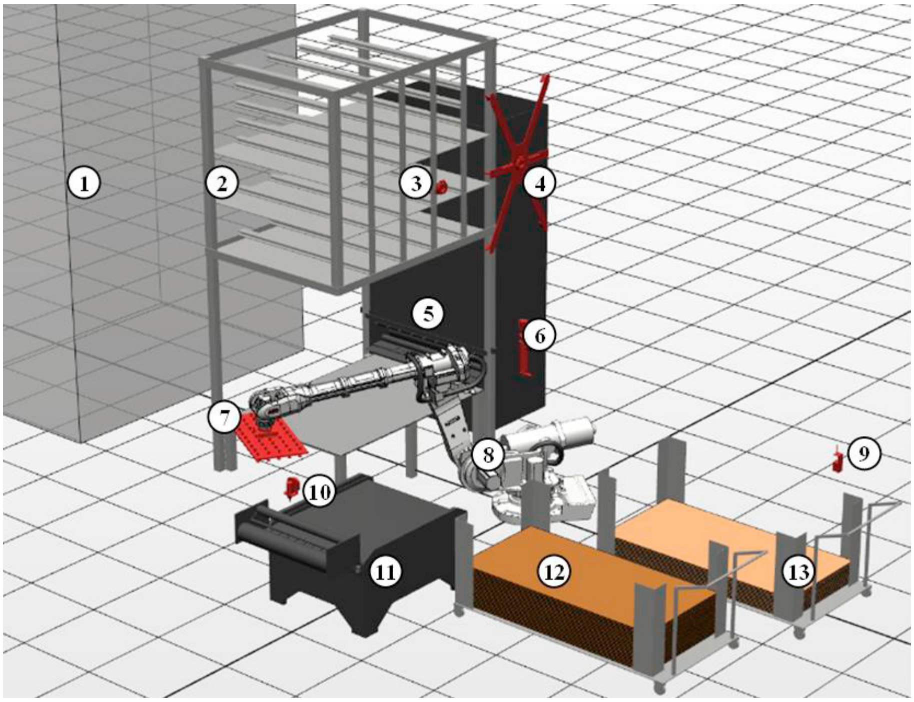

Fig. 4: simulation model: press tower (1), storage (2), labeling tool (3), honeycomb gripper (4), paternoster storage (5), potting tool (6), matrix gripper (7), robot (8), inductive displacement sensors (9), ultrasonic knife (10), cutting table (11), honeycomb storage (12), panel storage (13)

Tab. 1: proecess times

Process step	Relative Time
Potting	██████████████████████████
Laying of prepreg strengtheners	██████
Laying of core, face sheets and release film	███
Removal of finished panel	██
Cutting of prepreg strengtheners	█
Quality assurance	█
Referencing	▌

5. Conclusion

In this paper, an optimized process chain for manufacturing of highly individual, flat honeycomb sandwich panels for aircraft interior in small batches has been proposed. A detailed plant concept was developed based on existing technologies for gripping, cutting and storing of the materials as well as potting and curing. Furthermore, the need for more detailed process knowledge of the potting process has been shown and an approach using law of Darcy has been suggested. The feasibility of the plant concept as well as achievable production rates and machine utilization was proven with detailed simulation. The economic efficiency of the concept has been analyzed based on a first estimate of costs and savings. An adaption of the component design is needed in order to implement the proposed manufacturing concept as well as to utilize further potentials for cost reduction, timesaving and quality improvements. Additionally an alternative plant layout based on supported manual layup should be considered in future work, since it yields further benefits regarding the implementation of the proposed process chain as well as automated potting in an existing manufacturing environment.

Acknowledgements

The work presented in this paper is being carried out in projects funded by BMWi - Germanys Federal ministry for Economic Affairs and Energy. The authors wish to thank Diehl Aviation and 3D ICOM for their help, support and invaluable cooperation during the project.

References

[1] Airbus S.A.S., Global Market Forecast 2017-2036: Growing Horizons.
[2] S. Black, Advanced materials for aircraft interiors, available at https://www.compositesworld.com/articles/advanced-materials-for-aircraft-interiors (accessed on June 18, 2018).
[3] M. Elkington, D. Bloom, C. Ward, A.P. Chatzimichali, K.D. Potter, Understanding the lamination process, in: Proceedings of 19th International Conference on Composite Materials, 2013, pp. 4385–4396.
[4] C. Grant, Automated processes for composite aircraft structure, Industrial Robot: An International Journal 33 (2) (2006) 117–121.
[5] T. Bitzer, Honeycomb Technology: Materials, Design, Manufacturing, Applications and Testing, Springer Netherlands, Dordrecht, s.l., 1997.
[6] US Department of Transportation, Federal Aviation Administration, AMT Airframe Handbook Vol. 1 (FAA-H-8083-31), 2012.
[7] A. Björnsson, M. Jonsson, K. Johansen, Automation of Composite Manufacturing Using Off-the-shelf Solutions, Three Cases from the Aerospace Industry, in: Proceedings of the 20th International Conference on Composite Materials, Copenhagen Denmark, 2015.
[8] A.P. Chatzimichali, K.D. Potter, From composite material technologies to composite products: a cross-sectorial reflection on technology transitions and production capability, Translational Materials Research 2 (2) (2015) 26001.
[9] A. Bjrönsson, Automated layup and forming of prepreg laminates, 2017.
[10] J. Pflug, B. Vangrimde, I. Verpoest, P. Bratfisch, D. Vandepitte, Honeycomb Core Materials: New Concepts for Continuous Production, Sampe Journal 39 (2003) 22–30.
[11] M.T. Kordi, M. Husing, B. Corves, Development of a multifunctional robot end- effector system for automated manufacture of textile preforms, in: International Conference on Advanced Intelligent Mechatronics, Zurich, Switzerland, IEEE, 2007, pp. 1–6.
[12] M. Szcesny, F. Heieck, S. Carosella, P. Middendorf, H. Sehrschön, M. Schneiderbauer, The advanced ply placement process – an innovative direct 3D placement technology for plies and tapes, Advanced Manufacturing: Polymer & Composites Science 3 (1) (2017) 2–9.
[13] Airbus S.A.S., Honeycomb cores, hexagonal of polyamide paper, phenolic resin bonded, cured, Blagnac Cedex France, 2014.
[14] Airbus S.A.S., Woven glass fiber reinforced thermoset prepreg (e.g. phenolic) Flame retarded (FST), Blagnac Cedex France, 2015.
[15] Andreas Björnsson, Jan-Erik Lindback, Kerstin Johansen, Automated Removal of Prepreg Backing Paper - A Sticky Problem, in: SAE Technical Paper, SAE International, 2013.
[16] M.N. Grimshaw, C.G. Grant, J.M.L. Diaz, Advanced technology tape laying for affordable manufacturing of large composite structures, in: International sampe symposium and exhibition, 2001, pp. 2484–2494.
[17] J. Kratz, P. Hubert, Anisotropic air permeability in out-of-autoclave prepregs: Effect on honeycomb panel evacuation prior to cure, Composites Part A: Applied Science and Manufacturing 49 (2013) 179–191.