Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 66 (2017) 113 – 118

www.elsevier.com/locate/procedia

1st Cirp Conference on Composite Materials Parts Manufacturing, cirp-ccmpm2017

Automated Stamp Forming of Continuous Fiber Reinforced Thermoplastics for Complex Shell Geometries

Bernd-Arno Behrens[a], Annika Raatz[b], Sven Hübner[a], Christian Bonk[a], Florian Bohne[a], Christopher Bruns[b], Moritz Micke-Camuz[a,*]

[a] *Institut für Umformtechnik und Umformmschinen (IFUM), Leibniz Universität Hannover, An der Universität 2, 30823 Garbsen, Germany*
[b] *Institut für Montagetechnik (match), Leibniz Universität Hannover, An der Universität 2, 30823 Garbsen, Germany*

* Corresponding author. Tel.: +49-511-762-4102; fax: +49-511-762-3007. *E-mail address:* micke@ifum.uni-hannover.de

---

Abstract

This research describes the development of a fully automated forming process of continuous FRP to assemble a down scaled battery tray for a plug-in-hybrid automobile. The paper presents the results of forming experiments and a restraint approach to avoid wrinkling, an FEM forming simulation to detect the wrinkling behavior, shear effects and temperature trajectories for the consolidation at the end of the forming step, and a multi material gripper-system used for handling and preforming. The gripper system is capable of handling continuous FRP in different states and features a pneumatic stamp to pre-drape the heated organic sheet.

Peer-review under responsibility of the scientific committee of the 1st Cirp Conference on Composite Materials Parts Manufacturing

Keywords: Stamp forming; organic sheet; double curved surface; wrinkling

---

1. Introduction

The importance of fiber-reinforced plastics in automotive lightweight design is steadily increasing due to their specific mechanical properties. In addition to the traditional application areas in the interior or components such as the bumper, more and more structural and semi structural parts are made of fiber-reinforced plastics. Currently, the use of fiber-reinforced plastics is mainly restricted to applications in the high-price segment and in small quantities. The development of large scale suitable manufacturing processes which can be integrated in existing plant technology is required to enable the usage of fiber reinforced plastics (FRP) in large scale automotive production. In order to conduct forming processes on conventional stamping presses, thermoplastic based semi-finished products should be used, because of their advantages due to their re-melting capability compared to thermoset-based materials. Fiber-reinforced thermoplastics can be shaped under elevated thermal conditions [1]. Impregnated and consolidated fiber sheets are called organic sheets. Organic sheets are commercially available and they are suited for forming operations with small cycle times.

1.1. Organic sheet forming

To form organic sheets, they must be heated to the forming temperature by means of radiation (IR), contact (heating plate) or convection heating (air circulated furnace). The recommended forming temperature according to the manufacturer is approximately 40 °C above melting temperature and below the decomposition temperature of the respective thermoplastic matrix material. The positioning of the hot, softened and thus moldable organic sheet must be carried out with a suitable handling system immediately after the forming temperature has been reached. After the organic sheet is positioned, the forming begins by closing the tool. The forming is enabled by the following forming effects: fiber elongation and yarn straightening (tensile stress along the fiber), inter ply slip (bending) and intra ply shear (tensile stresses transversely to the fiber in the fiber plane). By using

Peer-review under responsibility of the scientific committee of the 1st Cirp Conference on Composite Materials Parts Manufacturing
doi:10.1016/j.procir.2017.03.294

continuous high performance fibers, fiber elongation can be neglected. At the end of the forming step the material has to be re-consolidated under pressure. After cooling in the mold, the finished part can be removed.

Due to the contact with the relatively cold tool, the organic sheet cools down rapidly during the forming phase. The re-consolidation of the organic sheet must be avoided before completing the forming process, since the described forming effects are prevented by premature solidification of the matrix. As a result, fiber deflection at internal radii and fiber fractures at external radii can occur [2]. In order to prevent the rapid cooling, the forming tools are heated to a temperature of 50 to 150 °C below the processing temperature of the respective matrix material.

In the case of double-curved geometries, an additional shear strain occurs [3], which causes a high risk of wrinkling. This challenge can be significantly reduced by optimizing the semi-finished blank and applying a defined tensile stress during the forming process [2]. Restraining forces can be applied by using heated blank holder systems [4] or locally installed grippers [5].

1.2. Simulation of composite forming

In order to describe the draping of an organic sheet the shear and bending behavior needs to be determined properly. The shearing of the organic sheet depends on the shear stress and can be characterized with help of the picture frame test or the bias extension test [6]. Despite the different experimental setups, both methods produce comparable results [7]. The bending stiffness can be determined using the cantilever test, in which a stripe of the organic sheet is heated in an environmental chamber and the bending is measured [8].

In order to simulate the draping of an organic sheet, different methods can be applied. By means of a kinematic model a surface geometry can be examined regarding its drapability. A kinematic model is based on the assumption that the length of the fabric corresponds to the geometry it is draped on [9]. Its disadvantage is that temperature effects on the bending and shear properties are neglected. By solving the basic continuous conservation equations using the FEM, those can be accounted for. Different material models such as viscous-hyperelastic [5] or plasticity models [10, 11] are used in order to describe the forming behavior of the fabric and the thermoplastic material.

1.3. Handling of FRP

For a holistic view on automated large scale suited forming processes the handling of semi-finished products must be considered since the forming of heated FRP is time crucial and the complexity of robot assisted automated handling is often underestimated. However, industrial handling processes require the grasping step of a workpiece, followed by the handling and positioning step and end up with releasing the workpiece [12]. By means of a rigid and form-stable workpiece, many implemented handling operations succeeded using conventional robot-grippers, such as parallel or centric grippers. The dimensionally stable grasping, handling and releasing of soft and limp materials is difficult though [13]. In this case, woven fibers for lightweight manufacturing require special gripper-systems. On the one hand it is necessary to maintain the composites initial form. On the other hand, preform functionalities before the stamp forming step have to be provided [14, 15].

Reinhard et. al [16] developed a flexible gripper for grasping flat fiber structures by using a perforated suction plate with masks to close certain areas. This technology enables a grasping of different previously cut fabrics but does not qualify for pre-form functionalities. Other systems based on this principle use an elastic element and e.g. a draping roll to pre-form the textile. Thereby, the elastic element performs a compliant behavior and passive adaption to the surface [17]. Brecher et. al. [18] showed an approach to grasp a fabric using the finray effect in the so called octopus-gripper. The adaption of the several gripper arms is enabled by spring elements which are included into the arms. The fiber grasping is realized by rotatable mounted needle grippers. Further technologies focus on energy efficiency regarding the air permeability [19] as well as non-contacting grippers based on e.g. lateral Coanda ejectors [20].

Using these grippers it is often attempted to maintain the composites shape by means of covering large areas of the textiles surface. Due to this, the investigations in this paper are focused on organic sheet. Hereby, large contact areas are challenging in terms of great temperature losses. Therefore, it is important to develop a gripper which is able to maintain previously elevated temperature by e.g. infra-red radiation. However, this requires small contact areas with the cold gripper.

2. Experimental setup

The reference part in this research was a down scaled battery tray for a plug-in-hybrid automotive vehicle. The geometry of the forming tool is depicted in Fig. 1. The geometry consists of a 260 x 170 mm and 50 mm deep shell which features a step-geometry and a tunnel-geometry for an exhaust gas system. The flank angle of the side walls is 5°, the minimum radius in the bottom of the tray is 2 mm, the infeed radius is 10 mm and the tool off-set is 1.5 mm according to the thickness of the organic sheet. The forming tool can be electrically heated. The tool temperature during the forming process is set to 110 – 120 °C.

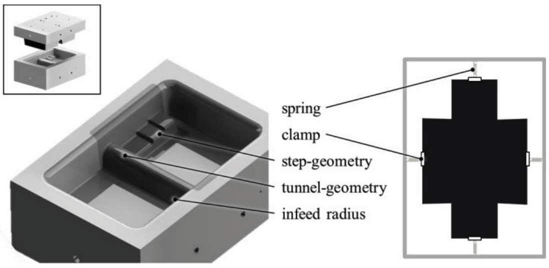

Fig. 1 Tool geometry and clamping frame

The forming process was carried out on a hydraulic press. The forming velocity was 40 mm/s and the pressing force was 1600 kN to consolidate the organic sheet at the end of the forming process.

The organic sheets consist of 0/90° and 45/45° woven glass fiber sheets with a polyamide 6 (PA6) matrix. The melting temperature is about 220 °C. The material thickness was 1.5 mm respectively.

The forming process consists of folding a cross-shaped blank into the shell and forming of the tunnel- and step-geometry. In order to feed the tool during the process the organic sheet is clamped centrally to all four sides by springs (Fig. 1). Throughout the forming process, the edges of the cross-cut are fluidly joined (butt-joint).

The used heating technology in this study is an infra-red (IR) radiator that elevates the organic sheet temperature to 260 °C within 45 seconds.

3. Numerical investigations

The simulation is set up and carried out with LS-Dyna, which allows the consideration of the fabric as well as the polymer matrix in one material model by averaging the stress states. In the draping process, the organic sheet is draped through a stamp and a die. The sheet is clamped by four metallic clamps on the sides, which are fixed in a frame (Fig. 2). In the simulation model, the clamps are modeled as rigid areas, which are connected by springs to a fixed joint. The stamp and the die are assumed to be rigid bodies. The initial temperature of the organic sheet is assumed to be 230 °C taking into account a possible loss of heat during the handling process. Due to the high heat capacity of the steel clamps, it is assumed that they are heated up to just 150 °C during the heating phase, which is taken as the initial temperature. In order to avoid a local cooling of the tools during the process, an artificial high density is assumed, which increases the heat capacity. The draping process is assumed to last ten seconds in total, from which the draping takes two and the consolidation eight seconds.

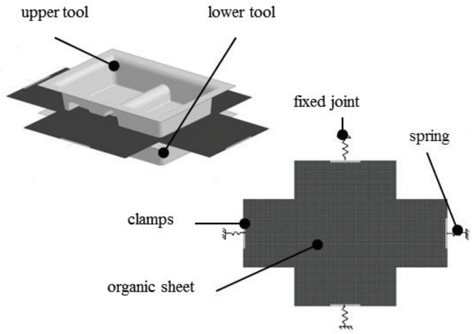

Fig. 2 Simulation model in LS-Dyna

4. Results and Discussion

4.1. Experimental and numerical results

While conducting forming experiments, it became certain that the desired organic sheet forming process is feasible. The folding and the joining process of the cross-cut edges as well as the restraining approach by using the clamping frame works reliable. Furthermore, the 5° flank angle of the side walls is sufficient to apply adequate pressure to re-consolidate the organic sheet at the end of the forming process.

However, the forming of the tunnel-geometry features major challenges regarding wrinkling and fiber fracture. Fig. 3 shows a series of the wrinkling behavior. On the left side the experimental results are illustrated. The right side shows the results of the numerical forming simulation. The carried out simulation proves to be suited to detect wrinkling behavior as shown. At 7 mm before the lower dead center (BDBC) of the forming process, the formation of the wrinkle is clearly visible. Since a necessary shear deformation is not possible due to the 0/90° orientation of the fibers, wrinkling occurs. In the further course, contact between the wrinkle and the tool (4.5 mm BDBC) occurs. The last stage shows the crimping of the wrinkle between the stamp and the die (3 mm BDBC).

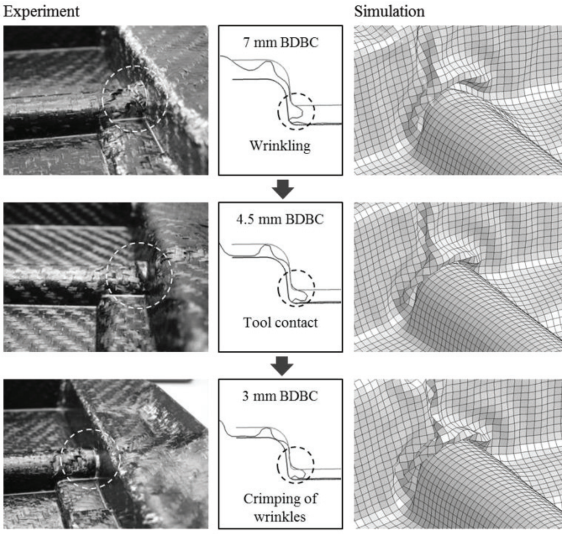

Fig. 3. Series of the wrinkling behavior, (organic sheet 0/90°)

At the end of the forming process, the wrinkle is not visible since the matrix material is displaced to the adjacent areas. This causes a fiber accumulation in the wrinkling area with a tripling of the material thickness. Since the tool off-set is constantly 1.5 mm, the wrinkling results in fiber fraction. Fig. 4 shows the area of the wrinkle after the formed part was re-melted. A re-melting of the formed part proves to be the fastest method to detect fiber fracture that is not visible right after the forming process. In Fig 4 with a 0/90° orientation fiber fracture is evident. By using a 45/45° fiber orientation the fracture can be avoided.

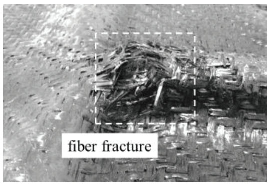

Fig. 4. Re-melted organic sheet part with unfolded fiber crimping area

In order to prevent fiber fractures by forming an organic sheet with a 0/90 ° fiber orientation, local fiber shear and yarn straightening can be induced by reducing the clamping width in the tunnel area. As shown in Fig. 5 the original clamping width of 6.5 mm was reduced to 1.5 mm which is approximately one half of the width of the tunnel-geometry.

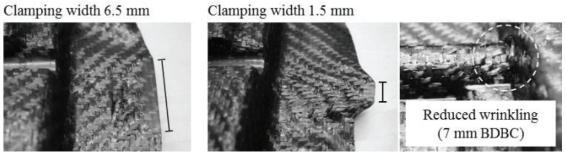

Fig. 5. Variation of clamping width (organic sheet 0/90°)

By inducing yarn straightening in load direction and intra ply shear of fibers transversal to the load direction, the surplus material to form the wrinkle is kept out of the forming tool. Thereby, the wrinkle formation can be virtually prevented and the cause of fiber fraction is eliminated.

Another challenge besides the double curved geometry is to supply enough material to form the tunnel. At the point where the tunnel geometry starts to form, which is depicted in Fig. 6, the side walls of the upper and lower tool are already parallel to each other. Due to the steepness of the walls, the material feed is aggravated. Furthermore, the organic sheet is stretched over the tunnel of the die, thus the material cools down rapidly and the forming effects are blocked before the end of the forming process. In the further course of the process, there is the risk of fiber tear in the corners of the tunnel geometry. The risk of fiber tear could be addressed by using a near net shaped semi-finished product or by pre-draping the tunnel before the actual forming process starts.

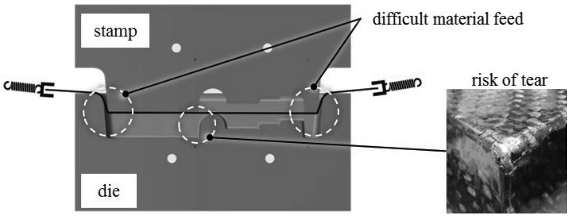

Fig. 6 Sectional view of the tool during the forming process

The results of the forming simulation regarding the temperature distribution are shown in Fig. 7. The temperature distribution inside the battery tray at the end of the draping phase and the temperature trajectories of specific areas are shown. It becomes evident that the bottom and the flank areas cool less quickly than the tunnel and the transition zone from tunnel to the bottom area. The latter comes into contact at an early point of the forming phase. Thus, all the surrounding areas are stretched over the corners of the upper tool, which leads to an increased heat transfer into the tool.

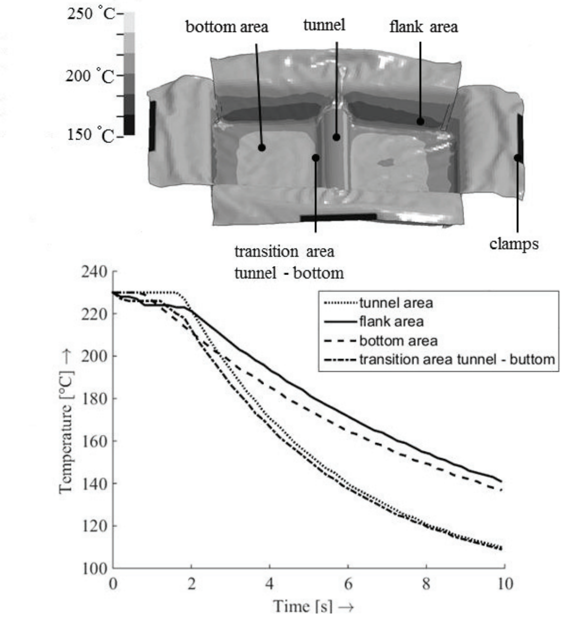

Fig. 7. Local temperature distribution over the tray

4.2. *Development of a gripper system with an integrated pre-draping punch*

To ensure a reliable forming process which would be able to form a battery tray with original dimensions instead of a down scaled test part, it seems to be necessary to pre-drape the tunnel geometry. Since the process forces to drape heated FRP sheets (organic sheets) are relatively low, the pre-draping step can be integrated into the gripper system to overcome forming issues. To pre-drape the material, the forming tool has to be set up upside down. In the following, the stamp was used as the lower tool.

A robot assisted handling of hot and limp organic sheets for feeding a stamp forming tool is challenging in terms of a fast material cooling rate. However, for a successful forming process, short distances between the used heating technology, the robot including its gripper as well as the forming tool are required. A major problem of the material is its low thickness in combination with the large surface which causes significant temperature losses due to convection. The robot-gripper consists of different grasping technologies to handle the organic sheet at various states (see Fig. 8). It includes vacuum-grippers to grasp the FRP while it is solid and an array of linearly guided special needle-grippers to grasp it at melting temperature.

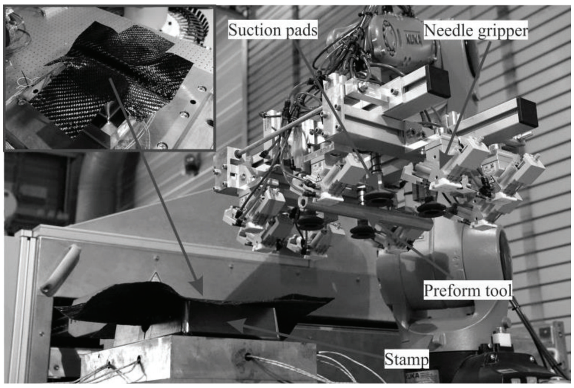

Fig. 8. Robot gripper system with suction and needle gripper and the preformed organic sheet on the stamp

At the beginning of the production process, the textile must be picked up from a material supply station at ambient temperature. Since, there are no certain requirements for coming into contact with the textile, conventional pneumatically telescopic suction pads are provided. Afterwards, the robot places the textile inside the IR-radiator for melting the polymer matrix. When the temperature of 260°C is reached, the non-rigid organic sheet is removed by specially coated needle grippers. These needle grippers are integrated at the circumference into the gripper system. To overcome the issue of high stresses and fiber failures in the tunnel area of the battery tray, a pneumatically telescopic round stamp is used to pre-form the tunnel by the gripper. The reason for a preforming directly on the forming tool is essential, because otherwise certain areas on the composites might harden at too low temperature. This causes fiber failures as well. Therefore, a previously preforming, as with dry fibers, is barely possible without reheating the entire composite. The idea of using a fast handling and combined pre-form/ stamp-form process enables a "once heating" process sequence. The entire process chain from the cold and rigid organic sheet to the fully 3D shaped battery tray can thus be performed. However, not only a secure handling at different temperatures by the robot is crucial for success. Another important parameter is the temperature distribution inside the organic sheet. For this reason the temperature of the entire organic sheet after preforming is thermographically measured. Figure 9 shows the thermogram of the composite on the stamp of the forming tool. It is apparent that the composite temperature is different weather it is in contact with the forming tool or not. Since metal conducts heat quickly, these areas are important for a successful shaping.

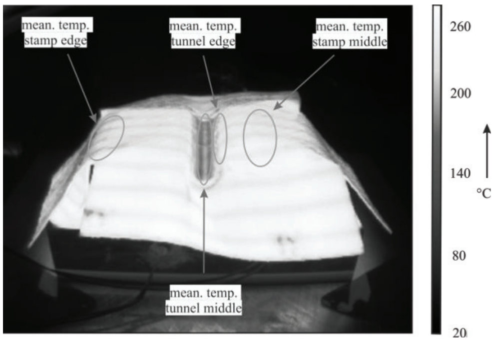

Fig. 9. Temperature distribution of the organic sheet after preforming on the heated stamp with the crucial areas for a successful stamp forming

As shown in Fig. 9, there are four areas for measuring the cooling rate. Three areas of the composites which stay in contact with the tool and one non-contact area were utilized for temperature observation. The tunnel bottom and edge are important because they were clamped by the forming and the preforming tool. This favors a rapid cooling. To minimize a temperature decrease in the tunnel area, both the stamp and the preforming tool are heated to 110°C. Another significant location is the edge of the stamp. At this point, gravity keeps the composite in contact with the tool. An area in between the tunnel and the edge of the stamp which has no contact to the tool was set as a reference measurement.

The used organic sheet consists of a polyamide 6 matrix with a melting temperature of 220°C. As a result, Fig. 10 shows the temperature profile of the four measuring areas after pre-forming.

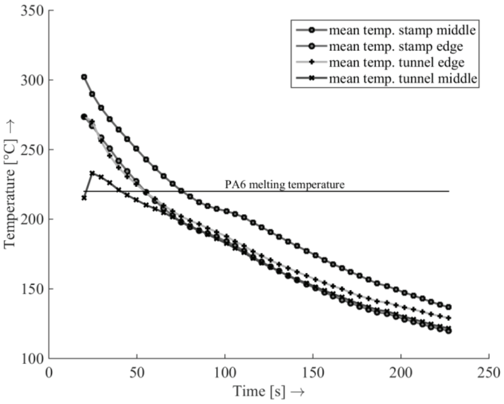

Fig. 10. Organic sheet cooling rate after preforming according to Fig. 9

At the beginning, the temperature distribution is spread from 240 °C to 300 °C. The mean temperature of the middle of the stamp shows the slowest cooling as expected. At areas which stay in contact with the tool, such as the tunnel and stamp edge, a faster cooling occurs. Especially the mean temperature of the middle of the tunnel shows the fastest cooling caused by the tool contact on both sides. Without using a preheated pre-form and stamp forming tool, the surface temperature of the tunnel decreases to 160 °C immediately after releasing the preform tool. This is far below melting temperature. Since both of the surface sides solidify due to the tool contact, a brief spring back of the preformed tunnel contour occurs. For this reason, using preheated tools shows an initial temperature of 240 °C that is suitable for a subsequent stamp forming. The temperature gradient of the tunnel middle is similar to the stamp and tunnel edge. However, the higher temperature leads to a greater spring back effect, caused by the woven fibers of the molten organic sheet. Therefore, it is most important to adjust a practical tool temperature. A tool temperature far below melting temperature causes a fast cooling of the polymer matrix and prevents a successful stamp forming. On the other side, a temperature near or above melting temperature leads to an adhering of the organic sheet to the tool surface and pulls the preform off the stamp after releasing the gripper.

5. Conclusion

This research shows the development of an automated stamp forming process on the example of a battery tray and associated forming simulation. The forming process features major challenges regarding wrinkling behavior due to double curved geometries and risk of tear caused by an aggravated material feed. The forming simulation carried out with LS Dyna proves to be valuable while forecasting the wrinkling behavior of organic sheets.

The paper presents approaches to solve the wrinkling and fracture issues. Fiber fracture caused by crimping of wrinkles could be avoided by:

- Inducing local fiber shear and yarn straightening to withdraw the surplus material out of the wrinkling zone.
- Using a 45/45° fiber orientation instead of a 0/90° orientation to avoid fibers orthogonal to the wrinkle.

In the case of blocked forming mechanism during the forming of complex shell structures a pre-draping process of the heated organic sheet seems to be promising. Therefore, a pneumatically actuated pre-drape-tool was integrated into the gripper to form the tunnel-geometry to avoid fiber fracture. This approach utilizes the interaction between handling and forming to manufacture complex FRP shell parts.

Acknowledgements

This research and development project is funded by the German Federal Ministry of Education and Research (BMBF) within the Forschungscampus "Open Hybrid LabFactory" and managed by the Project Management Agency Karlsruhe (PTKA). The author is responsible for the contents of this publication.

References

[1] Behrens B.-A., Hübner S., Neumann A., Forming sheets of metal and fibre-reinforced plastics to hybrid parts in one deep drawing process. Procedia Engineering 81 (2014) 1608 – 1613

[2] Bhattacharyya, D.: Composite Sheet Forming. Elsevier Science B.V.. 1997.

[3] Keilig, T., Determination of the forming behaviour of fabric prepregs depending on the type of fibre reinforcement and matrix using an appropriate rheological material model, DLR Deutsches Zentrum fur Luft- und Raumfahrt e.V. – Forschungsberichte, Issue 24, 2005, Pages 1-172

[4] Hinenoa, S., Yoneyamaa, T., Tatsunoa, D., Kimuraa, M., Shiozakia K., Moriyasub, T., Okamotob, M., Nagashimab, S., Fiber deformation behavior during press forming of rectangle cup by using plane weave carbon fiber reinforced thermoplastic sheet, Procedia Engineering 81 (2014) 1614 – 1619

[5] Guzman-Maldonado E, Hamila N, Naouar N, Moulin G, Boisse P, Simulation of thermoplastic prepreg thermoforming based on a visco-hyperelastic model and a thermal homogenization. Materials and Design 93; 2016, p. 431-442

[6] Lee W, Padvoiskis J, de Luycker E, Boisse P, Morestin F, Chen J, Sherwppd J. Bias-extension of woven composite fabrics. Int J Mater Form 1; 2008. p. 895-898

[7] Taha I, Abdin Y, Ebeid S,. Comparison of Picture Frameand Bias-extension Tests for the Characterization of Shear Behaviour in Natural Fibre Woven Fabrics. Fibers and Polymers; 2013, Vol.14, No.2. p. 338-344

[8] Liang B, Hamila N, Peillon M, Boisse P. Analysis of thermoplastic prepreg bending stiffness during manufacturing and of its influence on wrinkling simulations. Composites Part A 67; 2014, p. 111-122

[9] Cherif C.Textile Werkstoffe für den Leichtbau. Springer-Verlag Berlin Heidelberg; 2011

[10] Behrens, B.-A.; Vucetic, M.; Neumann, A.; Osiecki, T.; Grbic, N. (2015): Experimental test and FEA of a sheet metal forming process of composite material and steel foil in sandwich design using LS-DYNA, 18th International ESAFORM Conference on Material Forming, 15.04.2015 – 17.04.2015, Graz, Key Engineering Materials Vols. 651-653 (2015), pp 439-445

[11] Behrens, B.-A.; Grbic, N.; Bouguecha, A.; Vucetic, M.; Neumann, A,; Osiecki, T. (2015): Validation of the FEA of a Sheet Metal Forming Process of Composite Material and Steel Foil in Sandwich Design, WGP Kongress, 07.09.2015 – 08.09.2015, Applied Mechanics and Materials Vol. 794 (2015) pp 75-80

[12] Fantoni G., Santochi M., Dini G., Tracht K., Scholz-Reiter B., Fleischer J., Lien T.K., Seliger G., Reinhart G., Franke J., Hansen N.N., Verl A., Grasping devices and methods in automated production processes. In: CIRP Annals - Manufacturing Technology 63; 2014. p. 679-701

[13] Selinger G., Szimmat F., Niemeier J., Stephan J., Automated Handling of Non-Rigid Parts. In: CIRP Annals - Manufacturing Technology 52; 2003. p. 21-24

[14] Potluri P., Atkinson J., Automated manufacture of composites: handling, measurement of proporties and lay-up simulations. In: Composites, Part A: applied science and manufacturing 34; 2003. p. 493-501

[15] Rozant O., Bourban P.-E., Manson J.-A.E., Drapeability of dry textile fabrics for stampeable thermoplastic preforms. In: Composites, Part A: applied science and manufacturing 31; 2000. p. 1167-1177

[16] Reinhard G., Straßer G., Flexible gripping technology for the automated handling of limp technical textiles in composite industry. In: Production Engineering; 2011. p. 301-306

[17] Reinhard G., Ehinger C., Novel Robot-Based End-Effector Design for an Automated Preforming of Limb Carbon Fiber Textiles. In: Future Trends in Production Engineering (WGP); 2013.

[18] Brecher C., Emonts M., Ozolin B., Schares R., Handling of Preforms and Prepregs for Mass Production of Composites. 19 th International Conference on Composite Materials; 2013.

[19] Fleischer J., Förster F., Crispieri N.V., Intelligent gripper technology for the handling of carbon fiber material. In: Production Engineering; 2014. p. 691-700

[20] Lien T.K., Davis P.G.G., A novel gripper for limp materials based on lateral Coanda ejectors. In: CIRP Annals - Manufacturing Technology 57; 2008. p. 33-36