Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 66 (2017) 68 – 73

www.elsevier.com/locate/procedia

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

Influence of AFP process parameters on the temperature distribution used for thermal in-process monitoring

C. Schmidt[a], B. Denkena[b], T. Hocke[a]*, K. Völtzer[a]

[a] *IFW-Institute of Production Engineering and Machine Tools, Leibniz Universität Hannover, Ottenbecker Damm 12, 21684 Stade, Germany*
[b] *IFW-Institute of Production Engineering and Machine Tools, Leibniz Universität Hannover, An der Universität 2, 30823 Garbsen, Germany*

* Corresponding author. Tel.: +49-4141-77638201; fax: +49-4141-7763810. *E-mail address:* hocke@ifw.uni-hannover.de

---

Abstract

Automated Fiber Placement is an important manufacturing process when it comes to aerospace part generation. To minimize the machine downtime, an online monitoring system is necessary to prevent time consuming visual inspection. Therefore, a new thermal in-process monitoring system is integrated. Herewith spotted temperature difference enable the localization of placed tows and detection of defects. The thermal contrast between subsurface and tows depends on different process parameters such as lay-up speed, tooling temperature and compaction pressure. This influence is analyzed and discussed within lay-up studies to gain further knowledge about the different effects to increase the reliability of in-process monitoring as well as AFP processes.

Keywords: Automated Fiber Placement, Process Monitoring, Thermography

---

1. Introduction

The Automated Fiber Placement (AFP) is an important manufacturing process, especially for the part generation in lightweight industries such as aerospace applications. To minimize the machine downtime during the AFP process, an in-process monitoring system is necessary. Currently, the quality of each ply is ensured by a time consuming visual inspection carried out by the machine operator. Due to the low contrast between the black carbon fiber reinforced plastic (CFRP) slit tapes (tows) and additionally the complicated accessibility of the large components, the visual detection is very demanding. The resulting machine downtime including the defect correction takes up 32 % [1] to 65 % [2] of the production time. Furthermore, not detected defects will cause high repair costs if they are found first in the cured part during the non-destructive ultrasonic testing.

According to DIN29971 [3] the below listed defects are crucial for the production as well as for the quality assurance of composite structures:

- Positioning defects (gaps/overlaps) [4]
- Connection defects (bridging, air pockets) [4,5,6]
- Tow defects (splice) [4]
- Foreign bodies (fuzzball) [5]

In contrast, there is currently no monitoring system ready for use which is capable of detecting this defects reliably. Current research and development projects which consider to monitor the AFP process are using laser triangulation sensors, mounted behind the compaction roller, to determine the height profile of the placed course [7, 8]. Combining the sensor data with the position of the robot a three-dimensional height map can be build. The single profiles include information about the tow edges, the tow width and therefore also about the tow position. Defects such as spliced tows or overlaps can be determined and documented [7]. A first promising solution based on this measuring principle is tested in pilot production [9]. A disadvantage of this method is that it is affected by the subsurface geometry, especially regions of different laminate thicknesses might lead to wrong defect interpretations. The

doi:10.1016/j.procir.2017.03.220

laser triangulation concept is neither able to monitor the tack quality of the tows nor does it consider the fiber orientation that influences the reflection properties of the CFRP materials [10].

2. Description

Within the research project Therm-O-Plan, a thermal in-process monitoring system is developed [11]. The approach includes an infrared camera that records the occurring temperature distribution of laid-up cold tows and heated tooling surface. The two-part monitoring system localizes the tow positions based on an edge detection directly behind the compaction roller and detects temperature anomalies by analyzing the temperature distribution in defined Regions of Interest (ROI) (fig. 1). It is able to detect different kind of defects like foreign bodies, fuzz-balls or air enclosures [12].

Fig. 1. Thermal process image within the ROI.

The temperature difference and through this the thermal contrast between the heated subsurface and the cold tows depend on certain process parameters such as lay-up speed v_{AFP}, heater control temperature T_H and compaction pressure p_{AFP} (fig. 2). The previous approach of the monitoring system generates thresholds for the edge detection and surface inspection based on the actual temperature distribution in each infrared frame to determine the tow edges and detect occurring anomalies. Hence, defects that come with a continuous temperature change are difficult to detect, because the mean temperature of the ROIs are changing as well. To increase the reliability of the developed monitoring system, influences of named process parameters on the heat up and cool down behavior are discussed in this paper.

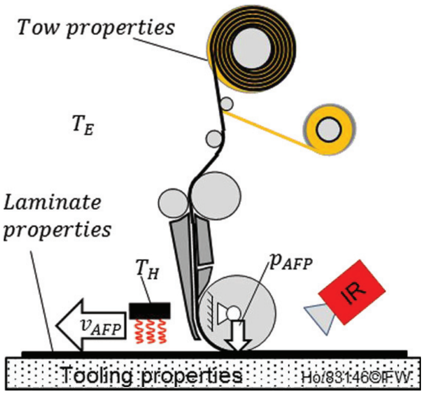


Fig. 2. Relevant process parameters for the AFP process monitoring.

3. Influence of AFP process parameters on the temperature distribution

3.1. Analytical Approach

The temperature behavior of the tows during the AFP process is composed to the superposition of the heat flow from the hot subsurface into the colder tows and the cooling effect of the interaction with the environment. Hence, the mean temperature profiles can be described as a double e-function:

$$T(s) = a \cdot \exp(b \cdot t) - c \cdot \exp(-d \cdot t) \tag{1}$$

Hereby, the parameters a, b, c and d of the thermal model depend on the process condition and parameters which will have an influence on the temperature distribution. The parameters are determined for each of the following experiments to plot semi-empirically fittings. In future, the aim is to determine the parameters depending on the process parameters to set up an analytical approach. This model can be used to generate thresholds online for a reliable process monitoring.

3.2. Experimental set-up

The experimental set-up to examine the influence of certain process parameters on the temperature behavior is shown in fig. 3. The aluminum tooling is isolated to the revolving table to store heat from the heating unit. Therefore, the tooling stays warm to ensure a good tack between the tows und the vacuum foil on top of the tooling. The in-house developed robotic AFP head is designed to lay-up four CFRP slit tapes in each course [13]. To realize the lay-up on complex surfaces, the compaction roller is separated into four single rollers. However, in this experiment a flat tooling is used to analyze the influence of one single parameter at a time (compaction pressure, heater control temperature, lay-up velocity). The same experiment will be repeated changing of only one parameter in the parameter configuration (Table 1). A three-ply [90°, 0°, 90°] laminate (680 mm x 680 mm) is laid up for each configuration. Previous experiments have shown that the influence of the laminate thickness does not change significant after the third ply. The environmental influences are nearly constant, the temperature in the experimental area is between 18.8 °C and 20.4 °C and the relative humidity is between 33 % and 40 %. Also the experimental set-up stays constant and the same CFRP slit tape material is used.

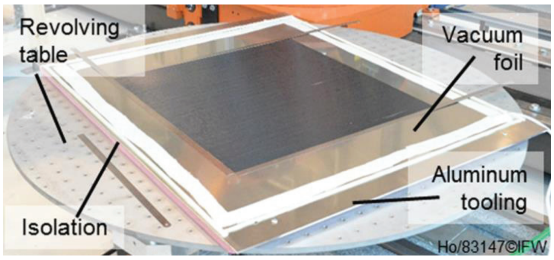


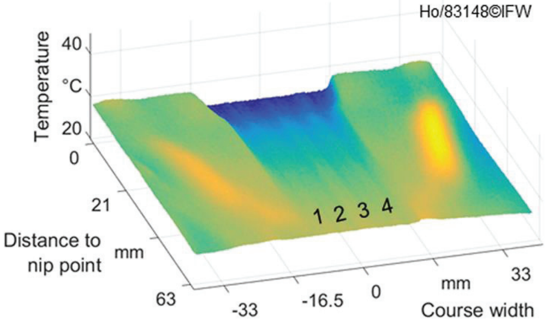
Fig. 3. Experimental set-up.

Table 1. Parameter configuration of the experimental set-up.

Number	Compaction pressure (*MPa*)	Heater control temperature (*°C*)	Lay-up velocity (m/s)
1	1.06	40	0.1
2	1.67	40	0.1
3	0.56	40	0.1
4	1.06	50	0.2
5	1.06	30	0.2
6	1.67	40	0.2
7	1.67	40	0.3

3.3. Influence of the path planning

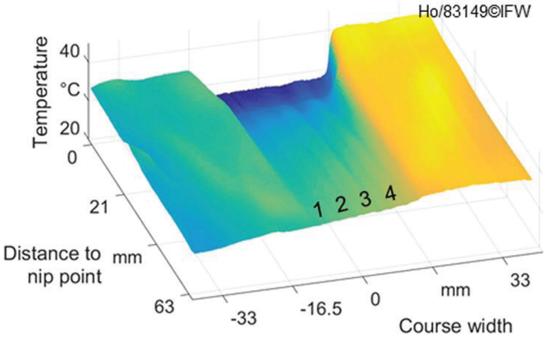
The path planning not only defines the ply book, the lay-up direction and planned gaps, it also affects the temperature distribution of the tows behind the nip point. The first course of the first ply shows a symmetric temperature distribution due to the fact that on both sides, left and right to the course, the surface detection analyses the symmetric temperature distribution on the aluminium tooling (fig. 4).



Ho/83148©IFW

Fig. 4. Temperature distribution in the first ply of course 1.

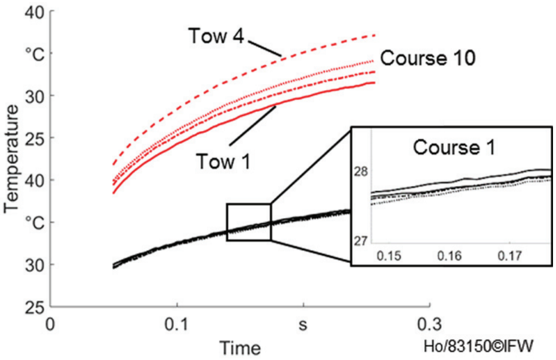
For all other courses the temperature distribution varies. Due to the different thermal properties of the aluminium tooling and the CFRP laminate, the previous placed tows store the heat and further influence the heat-up behaviour of the current placed tows (fig. 5).



Ho/83149©IFW

Fig. 5. Temperature distribution in the first ply of course 10.

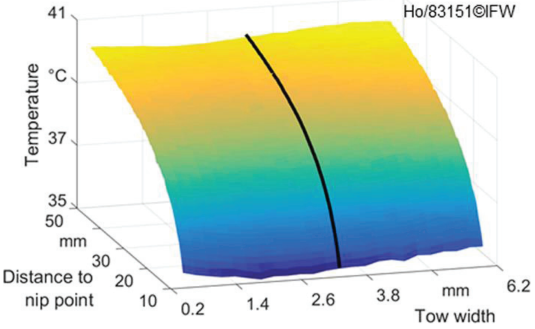
One course is laid up next to the other, so that the previous warm tows to the right of the current placed course cause a temperature gradient between the single tows within one course (fig. 6). The time-depended mean temperature profiles of the four tows of the first course in the first ply are similar. For all other courses (e. g. course 10), the temperature gradient cause, that the tows near to the previous course (e. g. tow 4) are warmer compared to the other tows (see also fig. 5). Furthermore, the tooling surface is getting warmer during the lay-up of each ply.



Ho/83150©IFW

Fig. 6. Influence of the path planning on the mean temperature profile.

Fig. 7 shows the mean temperature distribution of tow 4 for a whole ply. The mean temperature is nearly constant for different tow width. Hereafter, the small temperature gradient depending on the tow width is disregarded. To evaluate the experiments for all process parameter configurations and to compare the thermal behavior, the time-depended mean temperature profiles of tow 4 (comparable to fig. 7) is analyzed and the parameters of formula (1) are determined for each parameter configuration (table 2).



Ho/83151©IFW

Fig. 7. Mean temperature distribution for one ply of a single tow.

The corresponding temperature standard deviation increase with a longer distance to the nip point but the maximum temperature deviation is still smaller than 1.2 °C (fig. 8). The trend of the standard deviation equals the trend of the mean temperature so that the reliability of the thermal monitoring concept decreases with an increasing distance to the nip point.

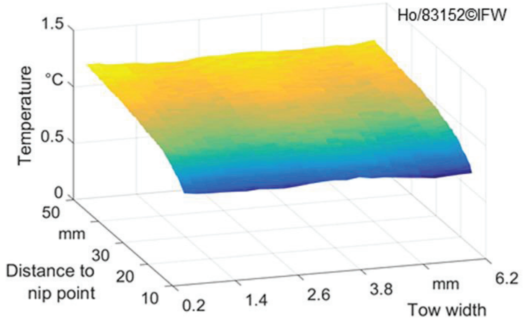


Fig. 8. Corresponding standard deviation of the temperature distribution.

3.4. Influence of the laminate thickness

The laminate structure issues the mechanical properties of the CFRP component. The fiber orientations significantly define the stiffness. It also influences the heat flow due to the fact that the thermal conductivity in fiber direction is higher compared to the thermal conductivity in through-thickness or cross direction. For this experiment only the laminate thickness matters. Therefore, the time-depended mean temperature profile including the standard deviation of tow 4 for each ply of the process parameter configuration 4 are shown in fig. 9. The aluminum tooling does not store the heat caused by the heater unit because of its high thermal conductivity and the large tooling surface. For this reason, the profile of the first ply is colder than the second and the third ply. Depending on the increasing laminate thickness the temperature profiles are warmer because the laid laminate stores the heat. This effect is not linear and transferable to the other parameter configurations. It affects the first plies till the laminate temperature stays constant. The standard deviation for all profiles is smaller than ± 1.2 °C and enables a reliable monitoring. Furthermore, the parameters of formula (1) are determined for each profile. In comparison with the measured profiles the semi-empirical model predicts the thermal characteristics of the profiles sufficient with R² of almost 1 (table 2).

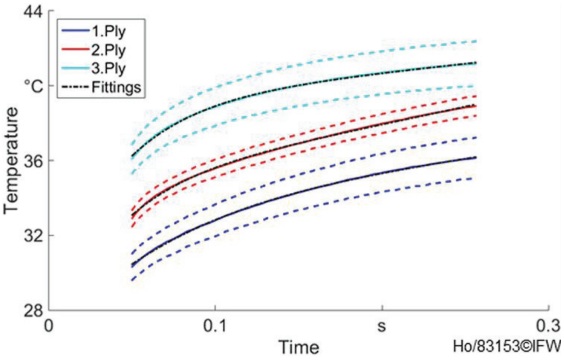


Fig. 9. Influence of the laminate thickness on the mean temperature profile.

3.5. Influence of the lay-up velocity

The infrared picture displays the placed tows and the subsurface next to the current course right behind the nip point. Hence, the lay-up velocity specifies the period of time from the nip point to about 50 mm lay-up length shown in each frame. A minimum lay-up velocity must be reached to ensure a thermal contrast. The maximum velocity depends on the AFP system and the time delay of the heat flow till the heat up behavior of the tow can be seen in the IR camera picture. The time-depended mean temperature profiles for different velocities do neither start nor end at the same point of time. Fig. 10 illustrates the mean temperature profiles of tow 4 in the third ply for the process parameter configurations 2, 6 and 7. Depending on the velocity, the plots start and end to different points of time. Despite the static temperature state after the compaction the mean temperature profiles do not merge. In this experimental set-up the lay-up velocity affects the amount of heat that is introduced into the laminate. The heat flow from tooling or laminate surface to the tow surface in through-thickness direction cause a time delay. Further experiments for more different velocities also need to be done to confirm the hypothesis. The semi-empirical double e-functions fits again to the mean temperature profiles.

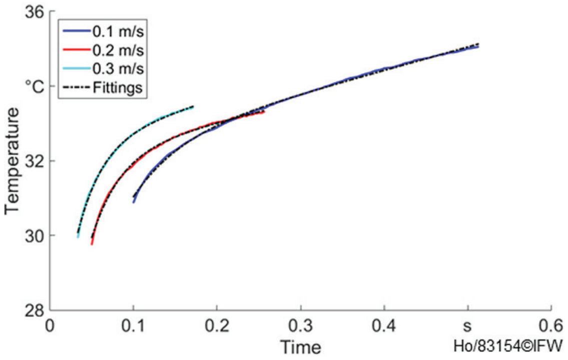


Fig. 10. Influence of the lay-up velocity on the mean temperature profile.

3.6. Influence of the tooling temperature

The tooling temperature affects the temperature distribution of the placed tows directly. Here, the heater control temperature is used to reach a higher or lower tooling temperature. Therefore, the maximum temperature the laminate can reach increases with a higher output of the heater unit. Fig. 11 illustrates the mean temperature profiles of tow 4 in the third ply for the process parameter configurations 4, 5 and 6. As mentioned before, the higher the control temperature the hotter the subsurface temperature which leads to a higher tow temperature. The plot of the mean temperature profile for the heater control temperature of 30 °C differs to the shape of the other two plots, because the temperature is too close to environmental temperature and the steady state is reached soon. This temperature is also the lower limit to get a minimum thermal contrast. The higher limit results from the properties of the thermoset prepreg, for manufacturing temperatures higher than 70 °C the resin viscosity becomes too low. Despite the significant influence of the heater control temperature on the mean temperature profiles, the parameters of temperature model are determined so that the half-empirically plots fits.

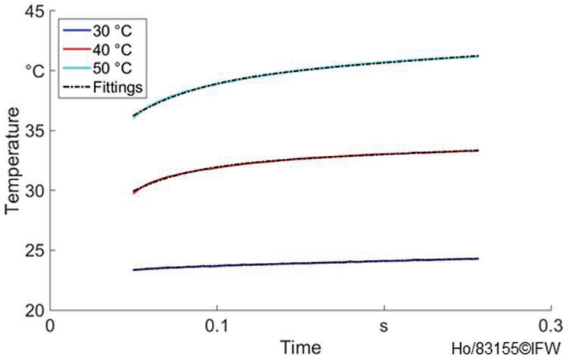


Fig. 11. Influence of the heater control temperature on the mean temperature profile.

3.7. Influence of the compaction pressure

The compaction roller ensures a good tack between the tows and the subsurface. Both the subsurface temperature and the pressure are responsible for the compaction and connectivity. Fig. 12 illustrates the mean temperature profiles of tow 4 in the third ply for the process parameter configurations 1, 2 and 3. The plots of the compaction pressures 1.06 MPa and 1.67 MPa are similar, only the temperature profile for the lowest compaction pressure is colder. Therefore also the determined parameters of the temperature model are nearly similar for 1.06 MPa and 1.67 MPa (table 2). The compaction pressure also influences the laminate quality which becomes worse in the first and second ply for low compaction pressures. Especially in the first ply, a high compaction pressure leads to a good tack and therefore to a good laminate quality. For thicker laminates the influence of the compaction pressure decreases significantly.

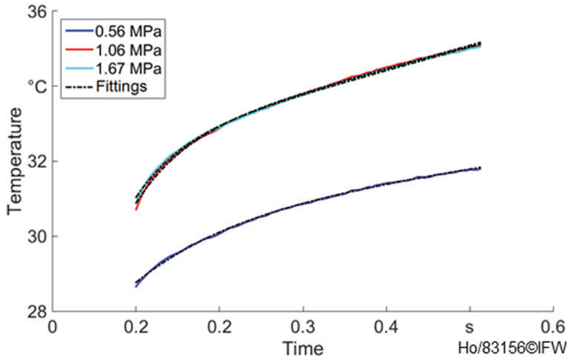


Fig. 12. Influence of the compaction pressure on the mean temperature profile.

Assuming a high quality in the first two plies the temperature of the third ply can be expected to be independent of the compaction pressure if a sufficient compaction is guaranteed (i.e. the plot for 0.56 MPa could merge the others). This hypothesis needs to be proved in further experiments where the compaction pressure is variated in the third ply for the lay-up on the same laminate. In addition, the minimum compaction pressures that guarantee a good laminate quality will be determined for different laminate thicknesses.

4. Results

The experiments demonstrate that certain process parameters influence the temperature distribution of the tows directly after the lay-up. Other process parameters only affect the temperature profiles for thin laminates or not at all. The laminate itself, especially the previous course, cause a temperature gradient depended on the tow width. The temperature distribution for a single process parameter configuration is very evenly with a small standard deviation. A rising laminate thickness leads to a laminate temperature closer to the heater control temperature. Therefore, the temperature profiles are warmer for thicker laminates. The lay-up velocity, as shown previously, does not influence the heat-up behavior significantly. The lay-up velocity defines which time range of the temperature profile is shown in the camera picture. This process parameter does not influence the heat-up behavior significantly, but the shape of the mean temperature profiles depends on the subsurface temperature mostly. Due to a non-constant heating power, the profiles do not merge at a certain point of time, but this effect is expected for a constant subsurface temperature. At the beginning of the heat-up process the shape of the profiles differ since the heat flow occurs time-delayed corresponding to the changing lay-up velocity. The heater control temperature affects the process directly and determines the maximum laminate temperature the temperature profiles are approaching. A minimum compaction pressure is necessary to ensure a good tack und therefore a high laminate quality. But for thick laminates a compaction pressure higher than this minimum compaction pressure does not influence the temperature distribution of the laid-up tows.

Table 2 lists the determined parameters of formula (1) for the shown mean temperature profiles of the experimental data. The shape of the double e-function fits all profiles within a high coefficient of determination higher than 99 %. Therefore, the analytical approach is able to forecast the temperature of the placed tows depending on the process parameters. Due to the small standard deviation of the mean temperature distribution within one ply the temperature model can already be used to generate thresholds online on the condition that the process parameters remain constant. During the first courses of each ply the parameter of the temperature model can be determined in order to forecast the temperature distribution for the following courses. Hence, the thermal online monitoring system generates thresholds online to ensure a reliable edge detection and surface inspection.

Table 2. Parameter of the temperature model for the half-empirically temperature profiles.

Number	Ply	a [°C]	b [1/s]	c [°C]	d [1/s]	R^2
1	3	32.14	0.176	9.13	16.12	0.999
2	3	32.06	0.178	9.01	17.31	0.999
3	3	30.34	0.098	4.20	8.09	0.999
4	1	33.89	0.283	7.53	13.06	0.999
4	2	34.50	0.479	8.72	27.12	0.999
4	3	39.00	0.220	10.57	24.06	0.999
5	3	23.37	0.152	1.05	33.94	0.996
6	3	31.96	0.166	9.48	28.50	0.998
7	3	32.31	0.207	7.37	33.03	0.999

5. Conclusion and Outlook

The temperature approach based on the double e-function of formula (1) can be used to determine and set the thresholds for the monitoring system depending on the process parameters and build the basis for a future temperature model. Fig. 13 shows the influence of the heater control temperature and the lay-up velocity on parameter “a” of the thermal model for the third ply of all experiments with a compaction pressure higher than 1 MPa. The final temperature of the heat up behavior (parameter a) increases depending on the heater control temperature and therefore with the subsurface temperature. Whereby the lay-up velocity does not affect parameter “a” significantly. The influence of certain process parameters on the thermal model need to be further investigated.

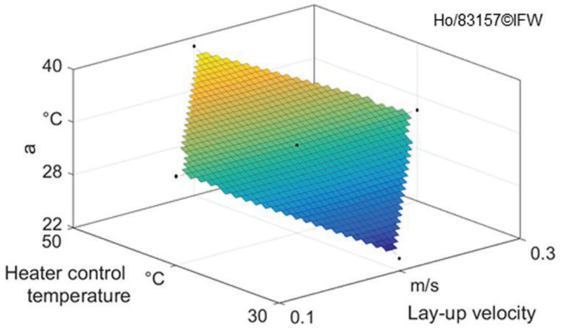


Fig. 13. Influence of the heater control temperature and the lay-up velocity on parameter a of the thermal model.

The process parameters based determination of threshold values allows the detection of temperature anomalies with a lower temperature deviation and helps to analyze characteristics of defects. The process parameters also influence the laminate quality depending on the position of the ply in the laminate leading to a variation of the process parameters for the first ply. For laminates with a thickness greater than a certain value, the process parameters can be set to known values. Further experiments are planned to validate the gained knowledge and to examine the influence of other parameters such as the material temperature. In addition, the hypothesis that the mean temperature profiles merge for different velocities and that all compaction pressures higher than the minimum required compaction pressure do also not influence the temperature distribution for thick laminates will be analyzed. Moreover, the planned temperature model to forecast the temperature distribution for certain process parameters will be the basis for a reliable and robust thermal online monitoring system.

Acknowledgements

The authors would like to thank the Central Innovation Program for SMEs (ZIM) for funding the research work “Therm-O-Plan” and the Niedersächsisches Vorab, Volkswagen Foundation for funding the research work “Multi-Matrix-Prepregs”. They also thank the federal state of Lower Saxony and the European Regional Development Fund (ERDF) for funding the preceding project HP CFK.

References

[1] Rudberg T, Nielsen J, Henscheid M, Cemenska J et al. Improving AFP Cell Performance. In: SAE International Journal of Aerospace Manufacturing and Automated Fastening Conference; 2014. p. 317-321.

[2] Halbritter A, Harper R. Big Parts Demand Big Changes to the Fiber Placement Status Quo. In: SME Composites Manufacturing 2012; 2012.

[3] Flemming M, Ziegmann G, Roth S. Faserverbundbauweisen. Berlin, Heidelberg, New York, Hongkong, London, Mailand, Paris, Tokio: Springer; 1999.

[4] Schulz M, Goldbach S, Heuer H, Meyendorf N. Ein Methodenvergleich – ZfP an Kohlefaserverbundwerkstoffen mittels wirbelstrom- und ultraschallbasierender Prüfverfahren. In: DGZfP – Jahrestagung; 2011.

[5] Alexandra K., Linb S., Brabandta D., Böhlkeb T., Lanzaa G.: Quality Control in the Production Process of SMC Lightweight Material, Bd. 47. In: Proceedings of the 47th CIRP Conference on Manufacturing, Bd. 47, S. 772 – 777.

[6] Lukaszewicz D H-J A. Optimisation of high-speed automated layup of thermoset carbon-fibre preimpregnates. University of Bristol, Bristol; April 2011.

[7] Maass D. Progress in automated ply inspection of AFP layups. In: Reinforced Plastics 2015; V. 59, p. 242-245.

[8] Nguyen C D, Krombholz C, Röstermundt D. Einfluss einer online Bahnkorrektur auf die Materialeigenschaften von Prepreg Tows im Fiber Placement Prozess. In: Deutscher Luft- und Raumfahrtkongress; 2012.

[9] Airbus Group. Airbus Group’s InFactory Solutions is delivering for the future with products and services for connected manufacturing; 2016.

[10] Stokes-Griffin C M, Compston P. A combined optical-thermal model for near-infrared laser heating of thermoplastic composites in an automated tape placement process. In: Composites Part A: Applied Science and Manufacturing (75), p. 104-115.

[11] Schmidt C, Völtzer K, Hocke T, Windels L. Automated path planning and thermographic monitoring for Automated Fiber Placement. In: Jec composites magazine; 2016, V.104, p. 76-78.

[12] Denkena B et al.: Thermographic online monitoring system for Automated Fiber Placement processes. In: Composites Part B: Engineering (97), p. 239-243.

[13] Denkena B, Schmidt C, Weber P.: Automated Fiber Placement Head for Manufacturing Innovative Aerospace Stiffenin Structures. In: Procedia Manufacturing; 2016, p. 96-104.