QUALIFICATION METHOD FOR AUTOMATED FIBRE PLACEMENT TO OPTIMIZE PROCESS PARAMETERS REGARDING LAYUP QUALITY

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Abstract: *Automated Fibre Placement (AFP) is an advanced process for the manufacturing of high-performance composite structures and is established in the aerospace industry. The main challenge is the optimization of the process parameters, such as layup speed, compaction force and heating temperature, to minimize the common AFP layup defects. The evaluation of these defects is an important topic during the development of new components. Defect detection is usually done by visual inspection of the layup and manual recording of the occurred defects. This paper developed a methodology to determine the defect characteristics, focused on out-of-plane wrinkles, which are typical during a curved layup of thermoset tape material in respect to process parameters, geometry and material width. This methodology offers the possibility to compare different materials and process parameters on a basic level to get a detailed understanding of the influence on layup quality within the AFP process.*

Keywords: Automated Fibre Placement; fibre steering; optical measurement; quality analysis; machine learning

1. Introduction

Due to their density-related and mechanical properties, composites are potential lightweight construction materials today and will continue to be so in future [1, 2]. However, their use in series applications poses enormous challenges for manufacturing technologies and can only be realised economically through a high degree of automation. The goal here is to substitute manual work steps with automated processes. Theoretically, this can be implemented for the entire process chain ranging from engineering and manufacturing to recycling. Automated fibre placement (AFP) is already being used and is part of this process chain. AFP is a highly automated process and therefore entails a high degree of complexity [3, 4]. For efficient use, this technology requires a comprehensive understanding of the process. This applies to engineering, manufacturing engineering and the production itself. There are a multitude of influencing factors (plant technology, materials, environmental conditions, etc.) that affect the manufacturing process and the perfect interaction of these factors results in the process window [5–7]. The determination of this process window is currently a time-consuming and manual process, which must be validated and adapted for new materials or new component geometries. The digitalisation of process variables and their further processing is one way of reducing complexity for the user, increasing process understanding and thereby establishing a robust process chain [8–10].

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To get an objective standard for the determination of the influences of different material, machine or environmental parameters a method was developed to qualify a standard layup for parameter evaluation using the AFP machine Csolo from the manufacturer Coriolis Composites. The outcoming qualification method consist of the AFP layup, its digitalisation and the algorithmic evaluation with the machine-learning algorithms and delivers as result the number of defects, the defect area and a self-defined quality parameter.

2. Methods

2.1 AFP experiments & material

The single-fibre AFP machine Csolo (Figure 1 left) from the manufacturer Coriolis Composites available at Fraunhofer IGCV was used for the lay-up trials. The machine can process thermoplastic, dry and thermoset tape materials in widths from ¼” (6.35 mm) to 1.5" (38.1 mm) [11]. To validate the qualification method, a serie of trials were carried out with the variation of different process parameters shown in Table 1. For each parameter configuration five individual tapes were laid-up inside of the scanning area of the optical measurement system (two sets per scan). As reference one single tow was laid up with no curvature, to get the nominal thickness of the processed material without any defects. In contrast to serial applications, no infrared lamp was used to heat the material. Instead, a heating plate was used to constantly preheat the lay-up surface to the desired temperature. The reason for this is the long heating rate of the infrared lamp and the resulting differences in the heating rate of the individual tows. The tooling was prepared with the lay-up foil Securelon® L-2000 from Airtech.

As material a typical aerospace thermoset carbon fibre prepreg in ¼” width, 0.2 mm thickness and an epoxy resin matrix was used. The material was manufactured within the tack life and stored in ambient conditions during the trials, regarding the AFP machine configuration.

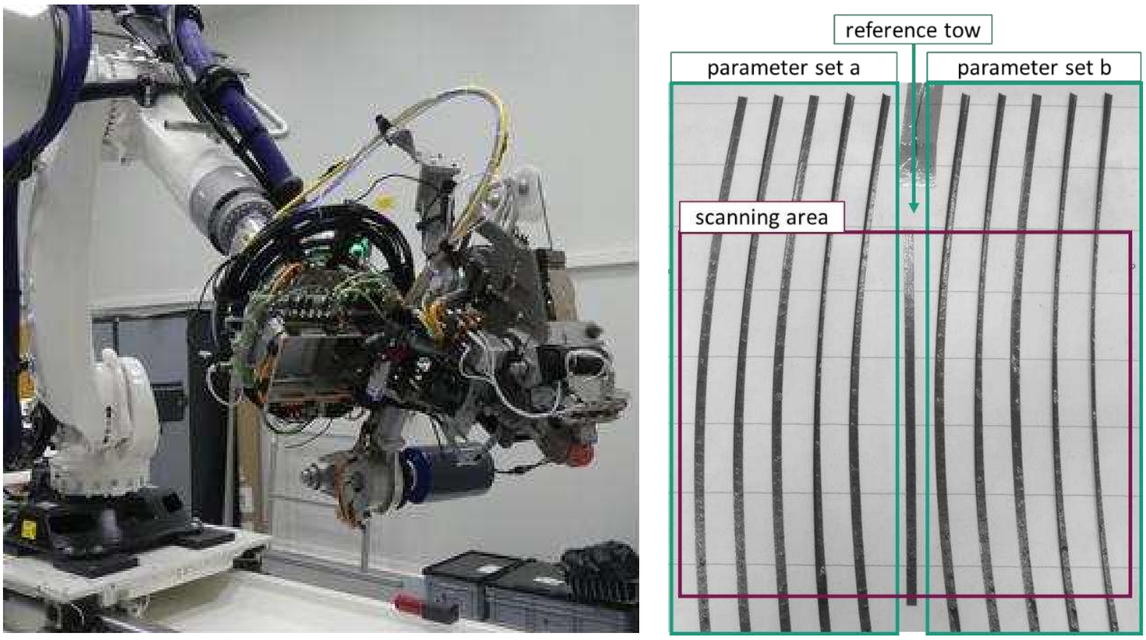


Figure 1. Csolo (Coriolis Composites) AFP machine (left), lay-up configuration of the experimental study used for two parameter sets, including the reference tow and the scanning area for the optical measurement system (right)

Table 1 : AFP process parameters and their variation step during the layup trials

Process parameter	Value	Step
Layup velocity [m/s]	0.04 – 0.2	0.04
Compaction force [N]	500	-
Tooling temperature [°C]	21.5 – 60	10
Layup radius [mm]	300 – 1500	300

2.2 optical measurement system

To generate the digital twin of the AFP layup for further processing and analysis of the quality, an optical 3D scanner is used. Herby different light patterns are used to generate a three dimensional shape of the surface. The 3D scanning sensor is the GOM ATOS Core 300 which combined two stereo cameras and a light source. The sensor operates with narrow-band blue light so that the distributing ambient light can be filtered by polarization. The measuring surface covers 300×230 mm and reaches a maximum resolution of 0.12 mm [12]. For geometrically complex or large-scale components, multiple scans must be performed and later superimposed using reference points. In order to avoid the effects of material reflections regarding the tape-surface on the scans, the surfaces is sprayed with an industrial matting developer.

2.3 point cloud processing

Since point clouds are usually noisy, sparse and unorganized, extracting features and information from them can be a very challenging task. A Python based approach was established using the point cloud library Open3D. Moreover the most relevant algorithms which were applied for this paper are the random sample consensus RANSAC (supervised) for the segmentation. RANSAC was developed for robust regression in data with noise. It is an iterative method for estimating a mathematical model from a data set that contains outliers. The RANSAC algorithm works by identifying the outliers in a data set and estimating the desired model using data that does not contain outliers [13]. In this paper the algorithm is used to segment the point cloud vertically. For this the point cloud containing n points is needed, then the algorithm picks at least 3 points to estimate a plane model. In the next step the distance between this plane and every other points is calculated. With the selected tolerance the classification of the points into inliers (inside the tolerance) and outliers (outside the tolerance) is performed. This routine is repeated until the set value of maximum iterations is reached. The chosen plane is the one with the highest value of inliers.

The second algorithm is the density-based spatial clustering of applications with noise DBSCAN (unsupervised) for the clustering of the generated point clouds. It relies on a density-based notion of clusters which is designed to discover clusters of arbitrary shape. It requires two parameters, the radius (Ɛ) of the sphere around the point and the minimum number of points (minPts) which has to be inside of this sphere. The algorithm creates a sphere with the specified radius around every point and classifies the points in three categories Core Point (number of points is bigger or identical as minPts), Border Point (number of points is lower than minPts) or Noise (no surrounding points). Afterwards the cluster is expanding, by randomly selecting a Core point and adding all Core points close to it (inside Ɛ), repeating this routine with all the added Core points as the next starting point. Border points are also added, but not used as starting points. [14]

3. Results

3.1 Layup quality qualification method

The outcome is a standardized routine, which starts from the layup and reaches till the algorithmic evaluation of the recorded point cloud to get the number of defects, the defect area and a self-defined quality parameter. The method considers all out-of-plane effects, like wrinkles, twists or tow pull off as defects. The routine is divided in the following steps:

- Apply the AFP Layup as shown in Figure 1
- Preparing the scanning area with matting developer to reduce the reflections on the tape surface
- scan the AFP layup with the ATOS Core 300 using the GOM Inspection software (Figure 2 left), the scan area of the layup was defined to the size of the one image in the ideal distance of the sensor ~300x230 mm and is shown in Figure 1 right
- Polygonise and export of the point cloud as ASCII using the GOM Inspection software to get a raw point cloud out of the scanned layup (Figure 2 right). The point cloud has its main coordinate system in respect to the sensor position.

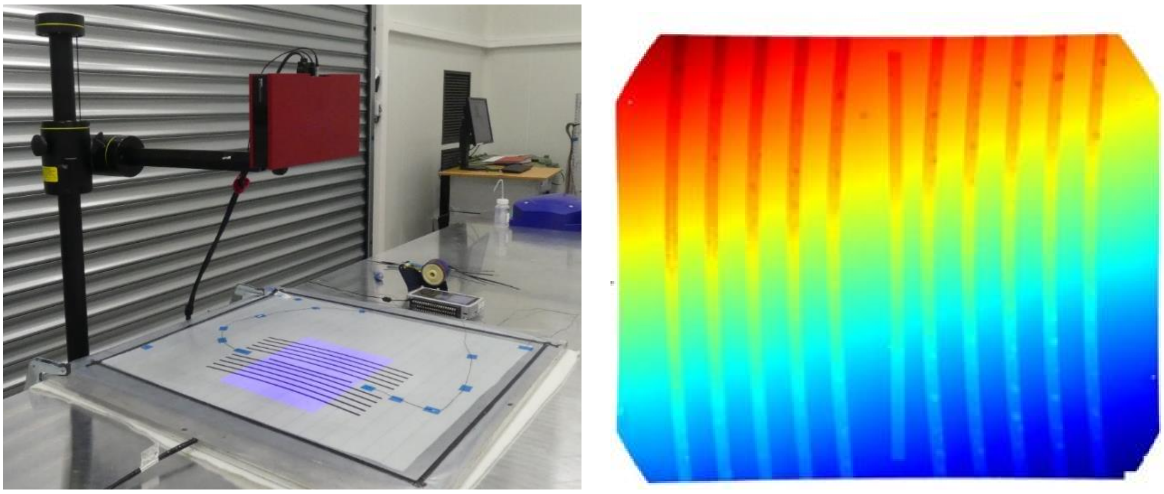


Figure 2. Setup of the scanning process using the GOM ATOS Core 300 (left) to generate a point cloud (right) for the algorithmic evaluation routine.

- Coordinate transformation using a fitted plane of the tooling surface to get a coordinate system in respect to the layup, z-direction will be layup direction (Figure 3 left).
- Segmentation of the steering ply from the tooling surface using the RANSAC algorithm with a tolerance considering the tape thickness (Figure 3 centre). The result is the tooling surface as inliers (Figure 3 centre, red area) and the tape surface and their defects as inliers (Figure 3 centre, green area).
- Clustering and labelling of the individual tapes with the DBSCAN (1) algorithm to separate them combined with their defects. To get rid of the noise clusters a minimum number of points was defined. (Figure 3 right)

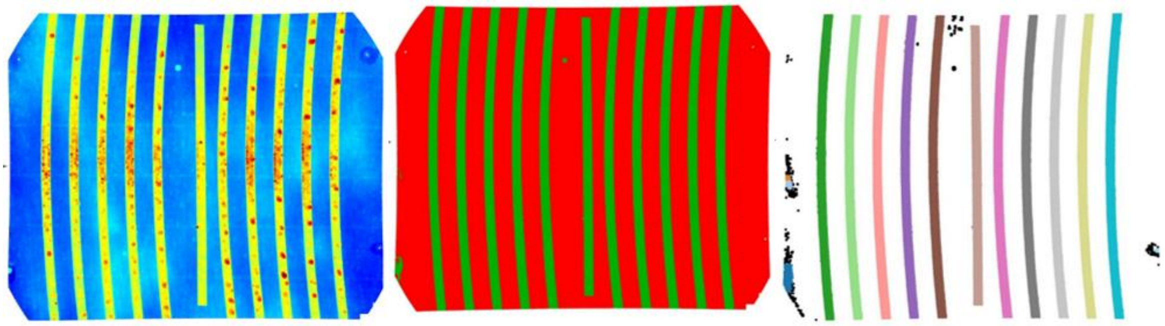


Figure 3. Individual steps of the algorithmic evaluation routine, coordinate transformation using a fitted plane (left), segmentation of the tapes and the tooling surface using RANSAC (centre), clustering of the individual tapes with DBSCAN

- Segmentation of the defect areas inside of the individual Tapes using the RANSAC algorithm to get defect area inside of the individual tapes
- Clustering of the individual defect areas with the DBSCAN (2) algorithm to separate the defects inside of one tape to get the number of defects
- Calculation of the defect size using a mesh generated with a ball pivoting algorithm

The parameters used for the algorithms are shown in Table 1 and are manually adjusted regarding the density of the point cloud and the thickness of the tape material.

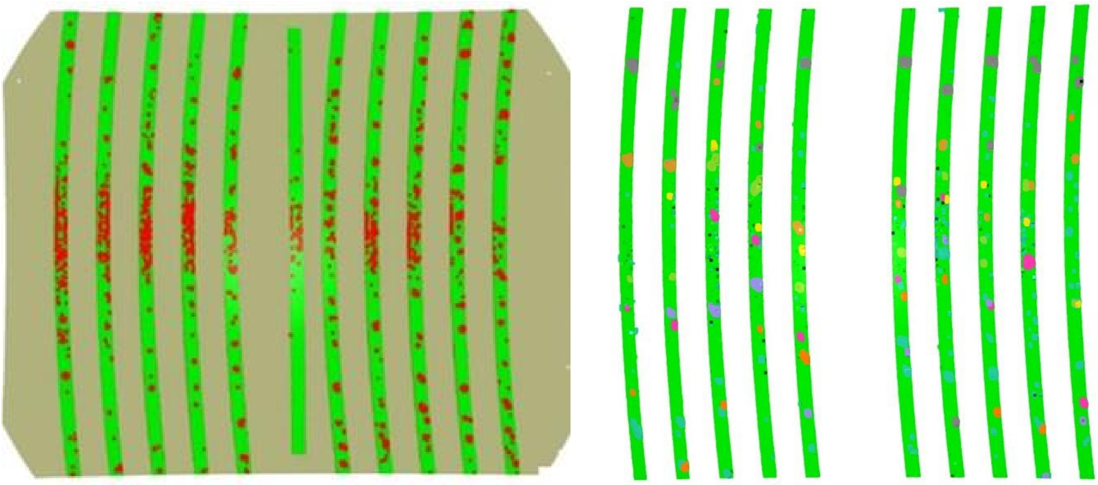


Figure 4. Using RANSAC to separate the defects from the tape area within the tolerance (left), clustering of the individual defects using DBSCAN (right)

Finally all calculations come together in the evaluation of the number of defects, the relative size of defects and the self-defined quality parameter. The quality parameter combines the defect area and the defect size relative to the mean value as shown in Eq.(1). This parameter considers a poor tape quality either with few huge defects or a large number of small defects and is a first approach to define such parameter.

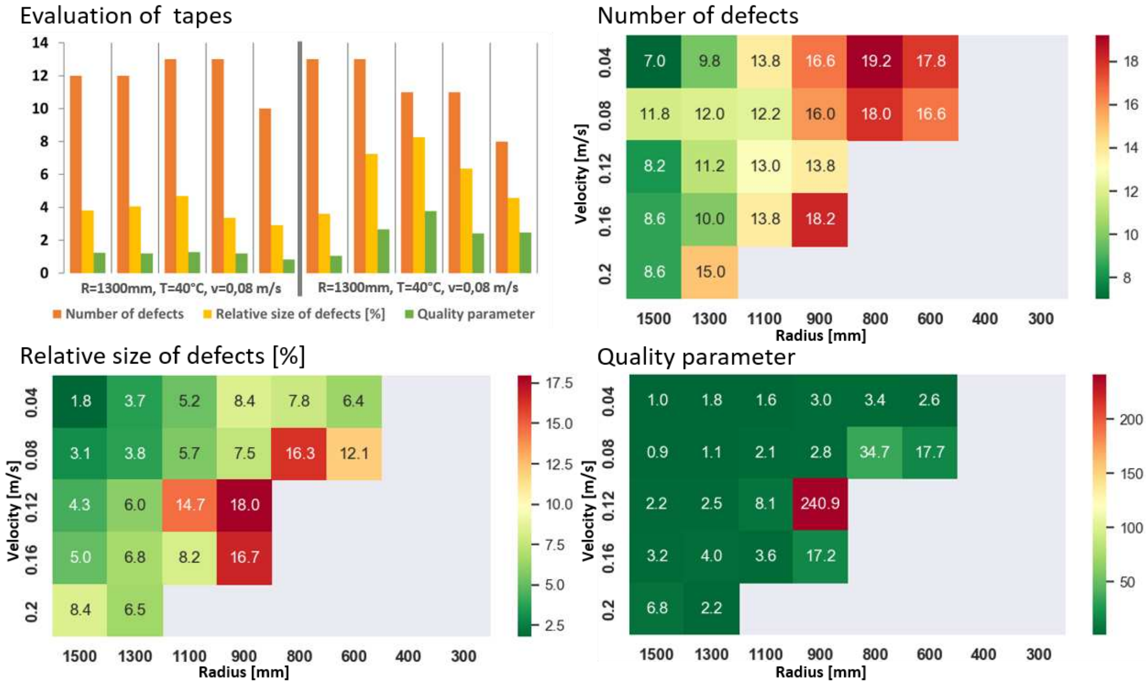
$$Q = X * R \; ; \; with \; X = \frac{z_{max}}{z_{mean}} \; and \; R = \frac{A_{defect}}{A_{tape}} \tag{1}$$

Table 2 : Parameters of the used algorithms

Algorithm	Parameter	Value
RANSAC	Distance tolerance	0.12
	RANSAC_n	3
	$\text{max}_{\text{iterations}}$	1000
DBSCAN (1)/(2)	Radius Ɛ	2.5 (1)/(2)
	minPts	100 (1); 20 (2)
Estimate normal KDTree	Radius	1.6
	$\text{N}_{\text{neigbours}}$	16
Ball pivoting	Radii	[0.7, 0.8, 0.9, 1]

3.2 Validation of the qualification method

To validate the qualification model a process parameter variation was performed and the routine was used for the evaluation. Figure 5 shows the evaluation of one experiment presenting two parameter sets and heat maps of all performed experiments on the tooling surface heated to 40 °C with the number of defects, the relative size of defects and the resulting quality parameter. If there is no value in the heat map it wasn't possible to perform a representing experiment due to no tack of the material within this process window.



Number of defects

Velocity [m/s]	1500	1300	1100	900	800	600	400	300
0.04	7.0	9.8	13.8	16.6	19.2	17.8		
0.08	11.8	12.0	12.2	16.0	18.0	16.6		
0.12	8.2	11.2	13.0	13.8				
0.16	8.6	10.0	13.8	18.2				
0.2	8.6	15.0						

Relative size of defects [%]

Velocity [m/s]	1500	1300	1100	900	800	600	400	300
0.04	1.8	3.7	5.2	8.4	7.8	6.4		
0.08	3.1	3.8	5.7	7.5	16.3	12.1		
0.12	4.3	6.0	14.7	18.0				
0.16	5.0	6.8	8.2	16.7				
0.2	8.4	6.5						

Quality parameter

Velocity [m/s]	1500	1300	1100	900	800	600	400	300
0.04	1.0	1.8	1.6	3.0	3.4	2.6		
0.08	0.9	1.1	2.1	2.8	34.7	17.7		
0.12	2.2	2.5	8.1	240.9				
0.16	3.2	4.0	3.6	17.2				
0.2	6.8	2.2						

Figure 5. Evaluation of two parameter sets for every individual tape (upper left) and of all experiments performed on the 40 °C heated tooling summarized over 5 tapes regarding number of defects, relative size of defects and quality parameter (bottom left and right side)

4. Discussion

Regarding to the qualification method, the main factors for the quality and accuracy of the method are the repeatability of the robotic system and the resolution and quality of the point cloud captured with the optical sensor. The robot repeatability and accuracy is the same as in the later manufacturing process so it is valid to use it within this method. In this paper the quality of the point cloud is next to the optical sensor also influenced by the needed industrial matting developer, which is applied manually. This human factor should be eliminated for further optimisation of the method. To reach this goal a laser scanning system described in [15–17] could be used. On the other hand the developed algorithmic evaluation routine is robust and could be used for similar point clouds of AFP layups of various machinery and sensor systems for point cloud generation with a sufficient resolution for AFP tape materials. Moreover it is applicable for out-of-plane defects, other AFP defects like in-plane waviness, tow drop or drift are not considered in the current status of the qualification method.

The results of the validation shown on every tooling temperature, that the relative size of the defects and the number of defects increase for higher velocities and smaller radii, like it is shown for example in [17, 18]. Another point is the investigation on different tooling temperatures, it shows first, that the number of possible process parameters increases with the temperature and second the number of defects decrease within the same parameter sets if the temperature is increased. From 50 °C to 60 °C there is a higher reduction of the defect number, in this case the point clouds show in-plane waviness occurred more than on any other tooling temperature and these defects couldn't be detected with the developed method. For the used material it means, that the viscosity changes significant over 50 °C and the steering leads to in-plane waviness instead of out-of-plane defects.

5. Conclusions

A qualification method for standardized AFP layups to detect out-of-plane effects and qualify them regarding their size and number including a self-defined quality parameter was developed. The method is based on the algorithmic evaluation of point clouds, captured with an optical measurement system, using different machine learning algorithms like RANSAC and DBSCAN. The validation showed that the method is applicable for the investigation of different process parameters like steering radii, velocity and tooling temperature and could be used for any other AFP process parameter or material variation. Regarding the Python and Open3D approach it offers the possibilities to integrate other analysis to implement the detection of further defects occurring during fibre steering. For research aspects it gives the opportunity to get a better understanding of fibre steering in an experimental manner and a possibility to compare it with simulation. Regarding digitalisation and automation of AFP production there is the opportunity to implement the method the AFP machine interface and define routines to check the status of the manufactured material or generate an ideal process window for various materials and conditions.

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