Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 85 (2019) 78–83

www.elsevier.com/locate/procedia

2nd CIRP Conference on Composite Material Parts Manufacturing (CIRP-CCMPM 2019)

Kinematic Description and Shape Optimization of UD-Tape Reinforcements Manufactured with a Novel Preforming Process

Daniel Kupzik*, Lukas Biergans, Sven Coutandin, Jürgen Fleischer

wbk Insitute of Production Science, Karlsruhe Institute of Technology (KIT), Kaiserstraße 12, 76131 Karlsruhe, Germany

* Corresponding author. Tel.: +49 1523 9502594; fax: +49 721 608-45005. *E-mail address:* daniel.kupzik@kit.edu

Abstract

The preforming of UD-Tape reinforcement structures for thermoplastic components can be done in additional process steps or during the handling processes. For an efficient process chain, it is desired to avoid non value adding steps like handling. Therefore they should be combined with value adding steps. A novel process for the preforming of UD-Tape strips has been developed at wbk Institute for Production Science to achieve this. In this process, the strips will be locally heated and bent by an industrial robot as they are pushed out of a material supply unit. With the process, it is possible to efficiently preform complex reinforcement tapes without the need for component specific tools. However, the limitation to local bending deformation sets process limitations different from the present, shear based processes. In this paper, an approach to the kinematic description and shape optimization of reinforcement patches is presented. First, a syntax for the description of tape strips containing several bends is presented. Afterwards, the kinematics of the process of bending tape strips around a bendable hinge are described. A method for pre-processing the geometry data of the desired structure with the aim of limiting the solution space is presented. Based on the kinematic description and the preprocessing of the geometric data, a genetic optimization environment for the bending parameters of a tape strip is implemented. The performance of the optimization shows its potential although the specific optimization parameters still have to be improved. Results and limitations of the optimization approach are presented.

Keywords: Algorithm; Composite; Flexibility; Handling; Optimization

1. Introduction

The combination of different material types in Multi-Material-Approaches is used in several fields of application in order to combine the advantages of the different material classes. A well-known example is the aluminum-steel combination in recent car manufacturing. Aluminum is used where high energy absorption capabilities are necessary or stiffness can be increased by casting. Steel can be used where high specific strength is desired. [1] This way, better performance can be reached than with a single one of the material classes at a lower cost. This concept can also be applied to fiber reinforced composite components. mechanical properties (stiffness, strength) improve with increasing fiber length and degree of orientation. At the same time, manufacturing cost and shape limitations increase with improved mechanical properties. Examples of such materials are unidiretionally reinforced Tapes (UD-Tapes), organo sheets and Long Fiber Reinforced Thermoplast (LFT). To utilize the advantages of different materials, wbk Institute of Production Science is participating in the International Research Training Group DFG 2078. In this Project, LFT components are locally reinforced with UD-Tapes. This way, the LFT's form filling ability will be combined with the stiffness of UD-Tapes. To fully utilize the individual advantages, it is necessary to place the reinforcement structures in highly loaded but geometrically simple areas of the component. The LFT will flow and fill the complex areas of the mold. It is usually necessary to preform the UD-Tape to ensure good quality [2, 3]. In this step, it has to be brought to a near net-shape geometry for the fixation in the mold and a good fit to the component's final design. A novel

10.1016/j.procir.2019.09.016

process has been developed at wbk for the preforming of thermoplastic UD-Tape stripes.

2. Bending based preforming

It is desired to integrate the preforming operations into handling processes to save cost and space for preforming stations. Several handling systems with prefoming capabilities already exist in the state of the art. Existing approaches use flexible robot grippers, which are pressed onto a mold [4, 5], or movable axes on the robot end-effector which can tilt and shift single gripping units and thereby deform the layup. These axes can either be placed specifically for the part [6–8] or in an universal way [9]. A specific placement enables a higher degree of forming, while an universal way is more flexible.
The requirements on preforming operations for reinforcement structures differ from those for fully unidirectionally reinforced components. For reinforcement structures, linear structures are formed, mostly by bending normal to their longitudinal axis. For full surface components, flat sheets have to be formed to fully three dimensional shells. An efficient integrated handling solution must be adapted to these specific requirements. Therefore, a bending based preforming process for reinforcements was designed at wbk Institute of Production Science. After preforming, the strips are assembled to a reinforcement structure.

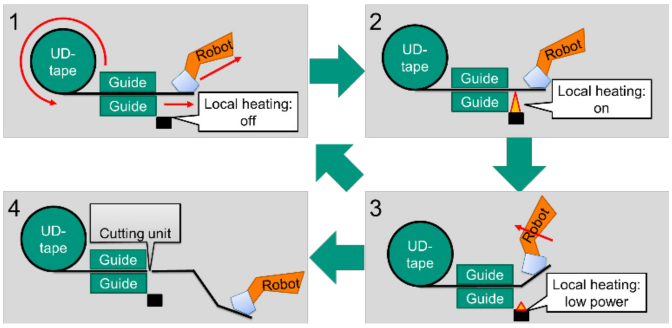

Fig. 1. Main steps of the integrated bending process

The strip's shape has to be determined by the movement of the robot to avoid specific tools or end-effectors. This way, a toolless and very flexible process is possible. To prevent unwanted deformation in a large heated area of the strip, the process is limited to bending in a local heating zone of the tape. During the bending, the tape is fixed in a supply unit on one side of the bending zone and guided by the robot on the other side of the bending zone. The main process steps (see Fig. 1.) are:

1. The UD-Tape is conveyed out of the supply unit. Afterwards, it is gripped by an industrial robot on it's far end.
2. The UD-Tape is locally heated. The heated area will be an area along the width of the tape with a diameter of about 2-5mm.
3. The robot is moving around the heated area while the heating unit will keep it in a molten state. The robot gripper can be released as soon as the tape has solidified.
4. Next, the tape will either be bent at the next position or cut off from the supply unit and laid down by the robot.

A pilot manufacturing cell has been implemented to further research the bending process. It is capable of bending up to 50mm wide UD-Tapes. The tape supply is driven by a stepper motor. The tape can be cut by a pneumatic cylinder and heated by an in-house developed radiation heater with a linear heating area. This heater is mounted to the robot-end effector. The bending moment is introduced through a pneumatic clamping gripper. The hardware is shown in Fig. 2. A video of the process is available at [10].

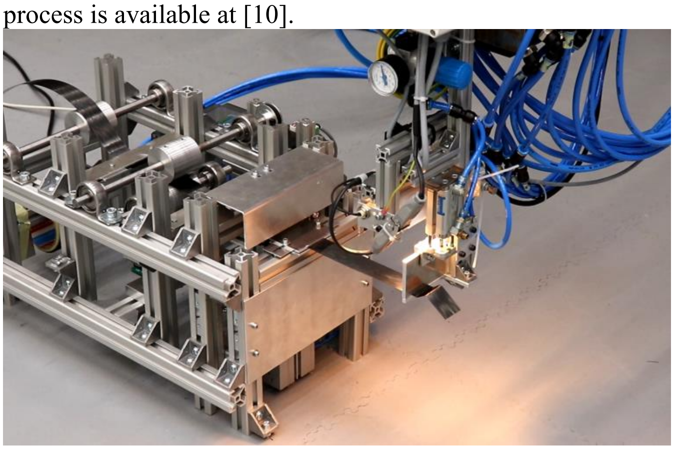

Fig. 2. Demonstrator cell for up to 50mm wide UD-Tapes

The novel process differs from existing processes in terms of process limitations. Obviously, no shear deformation in large areas of the tape is possible. This makes controlling the motion easier while limiting the degrees of freedom of the tape's shape. In order to utilize the process, an approach to derive the bending parameters needs to be developed. The input to this approach would be the desired patch position and shape in the final component. This desired patch properties often comes as a heat map with a ranking of the possible positions. One way how it can be derived is presented in [11]. The bending parameters will then be derived from this patch position and shape.

3. Optimization Algorithm

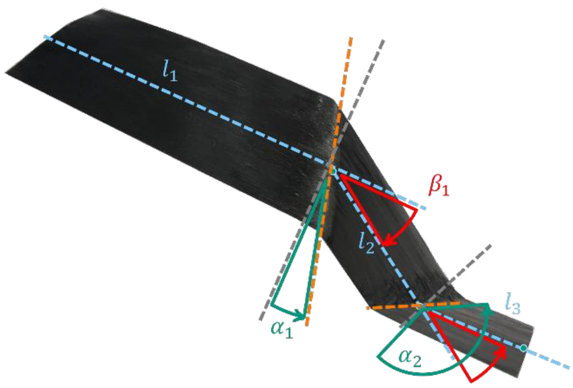

Fig. 3. Parameters for a bended tape

The aim of the algorithm is to determine the geometric parameters with which the robot should bend the tapes. The tapes must be bent in such a way that they are preformed as close as possible to the target shape. The input of the optimization is a CAD file of the surface of the target shape. For the described process the CAD file needs to be exported as STL file. The output of the optimization is a set of bending parameters with which the bending robot is able to bend the tapes.

First, it is necessary to define the bending parameters. Therefore a syntax for the description of bended tapes is needed Fig. 3 shows an example of a tape which is bent two times. The bending parameters are determined with the trajectory of the tape's centre line. Firstly, l_i determine the lengths of the sections between the bending edges. The angles α_i describe the rotation of the bending edge, since oblique-angled bending is considered. Finally, the angles β_i describe how far the tape is bent around the bending edge. Therefore, a tape with n bends can be described with $(3n + 1)$ bending parameters.

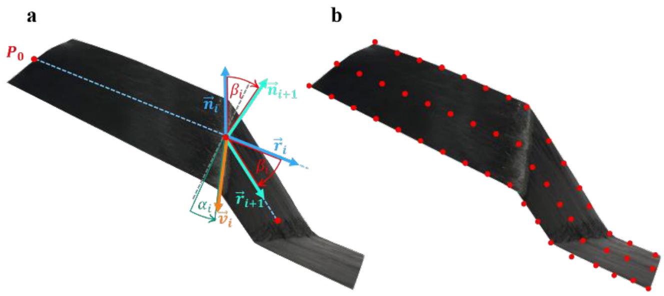

Fig. 4. (a) Kinematic description of an oblique-bended tape; (b) Parametrization with equidistant points

In order to optimize the bended tape, its position and geometry need to be compared to the target shape. At this point, a kinematic model is implemented to describe the shape of the bended tape with the bending parameters and to locate the tape in a three-dimensional reference system. With that model distances between the bended tape and the target shape can be calculated easily.

From a starting point $\vec{P}_0$, a starting direction $\vec{r}_1$ and a starting normal vector $\vec{n}_1$ which are yet to determine, the centre line of the tape can be parameterized in sections. A position x in the nth section on the centre line can be calculated with the following formula:

$$x(l) = \vec{P}_0 + l_1 \cdot \vec{r}_1 + \cdots + (l - \textstyle\sum_{i=1}^{n-1} l_i) \cdot \vec{r}_n \quad (1)$$

For each section of the bended tape, the direction vectors r_{i+1} must be calculated using the bending parameters l_i, α_i and β_i. First, an auxiliary vector v_i is calculated.

$$\vec{v}_i = R_{\vec{n}_i}(\alpha_i - \tfrac{\pi}{2}) \cdot \vec{r}_i \quad (2)$$

$R_{\vec{n}_i}(\alpha)$ is the rotation matrix corresponding to a rotation by an angle α about a fixed axis $\vec{n}_i$ [12]. With $\vec{v}_i$ the needed normal vectors and direction vectors can be calculated iteratively (see Fig. 4.a).

$$\vec{r}_{i+1} = R_{\vec{v}_i}(\beta_i) \cdot \vec{r}_i \quad (3)$$

$$\vec{n}_{i+1} = R_{\vec{v}_i}(\beta_i) \cdot \vec{n}_i \quad (4)$$

Additionally to the parametrization of the centre line, the side margins of the tape are parameterized accordingly.

This kinematic parametrization of a bended tape allows to calculate equidistant points on the tape which will be used to measure distances between the tape and the target shape (see Fig. 4b).

3.1. Objective function

In order to optimize the shape of a tape, an objective function must be set up. The aim of the optimization is to determine bending parameters which form the tape as close as possible to the target shape in order to prevent wrinkling and shifting of the tape in the molding process. In this paper, the objective function is modelled as a fitness function to be maximized. The fitness function consists of three sub-functions that try to quantize the quality of the tapes. One important quality criterion is that the tape does have the same length as the target shape. Therefore, the length sub-function fit_{len} aims to minimize the difference between the tape length L and a target length L_{target}, yet to determine.

$$fit_{len} = maxfit - k_l \cdot (L - L_{target})^2 \quad (5)$$

In this sub-function, a predefined maximal fitness value $maxfit$ is reduced depending on the squared difference. In this work, the same value for $maxfit$ has been used for all sub-functions and weighting has been done by the k and γ parameters. A penalty factor k_l is connecting the units of the length with $maxfit$.

Another important quality criterion is the average distance between the tape and the target shape. Therefore, fit_{dist} aims to minimize that distance. As in the previous sub-function, $maxfit$ is reduced, depending on the average distance $d_{average}$ between the points of the tape (Fig. 4 (b)) and the target shape. By dividing the average distance by L_{target} various geometry sizes can be considered. Accordingly to (5), k_d is the penalty factor.

$$fit_{dist} = maxfit - k_d \cdot (\tfrac{d_{average}}{L_{target}})^2 \quad (6)$$

Finally, in order to place and combine the tapes, the location of the starting and ending points of the target shape must be reached by the tapes. The following sub-functions aim to reduce the distance between the start and end of the target shape (P_{start},P_{end}) and the start and end of the tape's centre line (P_0,P_{n+1}).

$$fit_{start} = maxfit - k_p \cdot (|\overrightarrow{P_{start}P_0}|^2) \quad (7)$$

$$fit_{end} = maxfit - k_p \cdot (|\overrightarrow{P_{end}P_{n+1}}|^2) \quad (8)$$

All sub-functions are weighted and combined in one fitness function.

$$fit = \gamma_d \cdot fit_{dist} + \gamma_l \cdot fit_{len} + \gamma_p \cdot fit_{start} + \gamma_p \cdot fit_{end} \quad (9)$$

3.2. Optimization

An evolutionary algorithm approach has been chosen as optimization method. The advantages of not requiring the approximation of any derivatives or prior knowledge of the problem simplify the implementation. Therefore, evolutionary algorithms can be applied in complex problems like FEM-optimizations with a variety of variables [13] and the shape optimization presented here. As in the work of [14], the implementation of the evolutionary algorithm is based on an open source Python package for genetic algorithms, called Galileo [15]. The package contains the two classes Population and Chromosome which provide functions for initialization, selection, crossover, mutation and replacement.

In the initialization a population of chromosomes is created. For each chromosome the fitness is determined with the fitness function. Depending on the selection method a number of chromosomes is selected for crossover and mutation in which the parameters of the individuals are varied. In the replacement process a new calculation of the fitness of all individuals determines which individuals may survive. These steps are repeated multiple times in order to find better and better solutions from one generation to another.

All relevant parameters of an individual solution are coded as genes in a chromosome. The larger the number of genes in a chromosome, the larger the solution space of the optimization problem. To keep the computing power and duration low, the number of genes should be kept as low as possible. On the other hand, a certain number of genes is necessary to describe a bended tape. As mentioned before, a few parameters must be determined in order to calculate the fitness of an individual as well as to model a tape with given bending parameters. The starting point $\vec{P}_0$ and the starting vectors $\vec{r}_1$ and $\vec{n}_1$ must be given to parameterize a tape. Also, the number of bends has a big impact on the shape of the tape. Together with the bending parameters l_i, α_i and β_i, those missing parameters could be initialized randomly. However, the solution space would become very big and the chances of finding a global optimum would be very low. Finally, the calculation of the fitness needs a target length L_{target} which depends on the input geometry.

3.3. Pre-processing

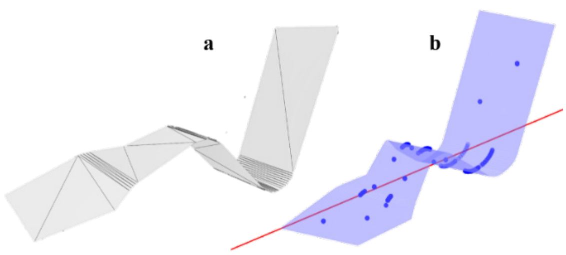

Fig. 5. (a) STL-file of a target shape; (b) point cloud of triangle centre points (blue points) and trend line (red), calculated from a singular-value decomposition of the point cloud

To reduce the solution space and to find required parameters for the fitness function, a pre-processing of the geometry data is developed. The aim of this pre-processing is to automatically analyse the STL-file to find L_{target} and to derive a starting solution which is then varied to create a starting population of chromosomes which already have a high fitness.

The target shapes are provided in the STL file format. Therefore, their geometry is described by a multitude of triangles (see Fig. 5a). The vertices and normal vectors of the triangles can be extracted easily from the STL file. However, the triangles listed in the STL file are not sorted. With the vertices a point cloud of the triangle centre points is created. In the point cloud, the triangle centres are weighted depending on the respective triangle area. Then, with a singular-value decomposition of the point cloud, a trend line can be calculated which aims to approximate all points in the point cloud (see Fig. 5b). This trendline gives a direction of propagation of the target shape and helps sorting the triangles.

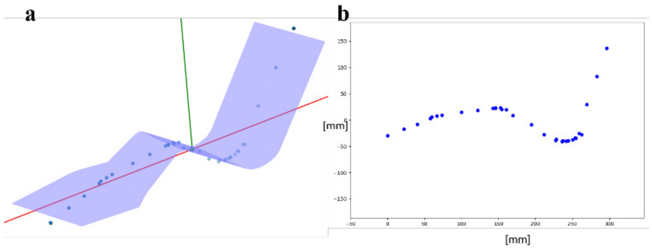

Fig. 6. (a) Centre points are projected in plane, defined by the trend line and the averaged normal vector (green); (b) two-dimensional projection

In the next step, an averaged normal vector of all triangles is determined. Together with the trend line and the data mean of the point cloud, the averaged normal vector defines a plane. The triangle centre points are now projected into this plane (see Fig. 6). Thereby, a two-dimensional curve shape of the target shape can be determined.

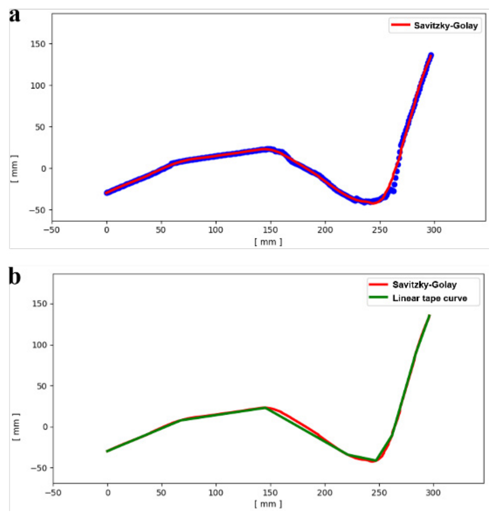

Fig. 7. (a) Savitzky-Golay filter curve (red) of the two-dimensional projection curve; (b) linear approximation (green) of the smoothing curve

The two-dimensional projection curve points are then filled with equidistant points and smoothed with a filter function (see Fig. 7a). In this work a Savitzky-Golay filter [16] has proven useful as filter function. By varying the convolution coefficients of the filter function, the shape of the smoothing curve can be influenced. The length of the smoothing curve is calculated and becomes the target length l_{target}, necessary for the calculation of the fitness function.

In order to create a starting solution, a two-dimensional shape of a tape must be derived from the smoothing curve. Therefore, the smoothing curve is linearly approximated in sections (see

Fig. 7b). With a defined maximum distance to the smoothing curve, a linear curve is created, which determines the number of bends of the tape and with which first bending parameters (l_i, and β_i) can be calculated. The rotation angles α_i are set to 0°, since the initial tape solution is two-dimensional. Also, starting point $\vec{P}_0$ and the starting vectors $\vec{r}_1$ and $\vec{n}_1$ are derived from the linear tape curve. The initial bending parameters are transcribed in a starting chromosome. Randomly generated variations of this chromosome create the initial population which is then optimized by the evolutionary algorithm (see Fig. 8). In the initialization and due to the probabilistic character of the crossover and mutation functions, the bending parameters are varied. Therefore, tape-solutions with $\alpha \neq 0$ can be created.

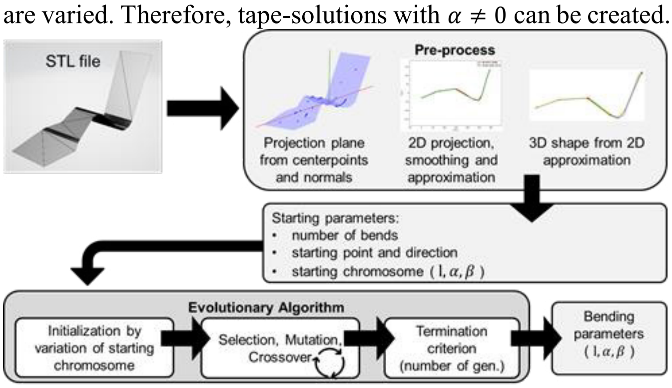

Fig. 8. Overall process of the tape shape optimization

3.4. Results

The algorithm has been developed and tested with multiple test geometries. Best results have been achieved with an *Elite Ranked Selection* as selection method, a *Flat Crossover* as crossover method and a *Uniform Mutation* as mutation method. Population size has been held below 40 and the number of generations below 200. A detailed examination of the genetic optimization itself still has to be conducted as the design of the optimization environment was in the focus of the previous work. In this paper, the results of two test-geometries are shortly presented. The result for the target shape of Fig. 5 are shown in Fig. 9 and Fig. 10.

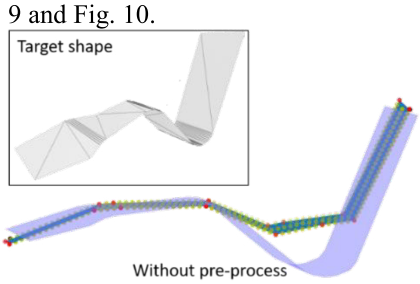

Fig. 9. Optimized tape without using the start bending parameters from the pre-process

For the tape in Fig. 9, the population has been initialized randomly, meaning the bending parameters l_i, α_i and β_i of the first generation of solutions have been randomly chosen, while number of bends, starting point and starting direction still have been adopted from the pre-process. Regarding Fig. 9, the optimized tape (dark blue) is able to approach the given target shape (light blue) and tries to minimize the distance to the target shape. Also, the start and end area are reached by the tape and the length of the tape approaches the length of the target shape. By this, the sub-functions of the fitness function and the convergence of the evolutionary algorithm can be validated. However, the optimized tape is not able to reach the lower curve of the target shape. It is assumed that the optimization has got stuck in a local optimum. The probability for leaving local optima is very low because there is a strong influence of single parameters on the shape of the whole patch. One example is that changing one bending angle will displace the whole following patch area. Therefore, it is very hard to have a bend in the model jump from one bended area across a flat region to the next bended area on the real part.

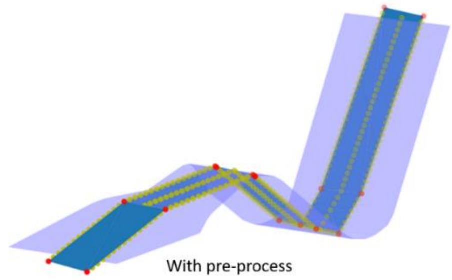

Fig. 10. Optimized tape using the start bending parameters from the pre-process

In Fig. 10, a tape which was optimized with the evolutionary approach after the preprocessing is shown. It is easy to see that the tape is now able to approximate the curve of the target shape. It is shown, that the combination of an analytic preprocessor with the evolutionary optimization is beneficial.

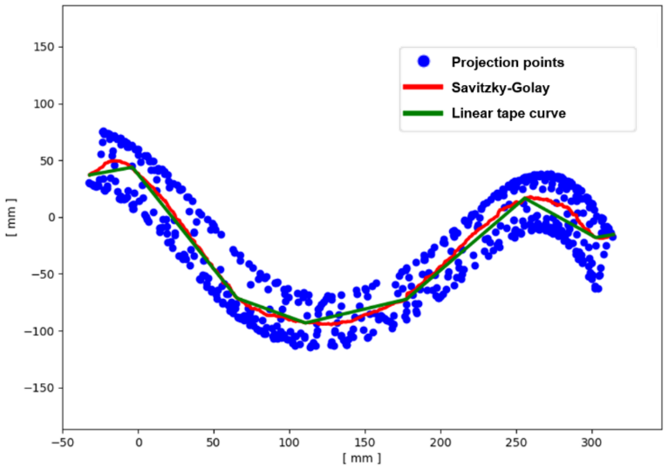

Fig. 11. The Savitzky-Golay filter curve approaches the projected triangle centre points. From the Savitzky-Golay curve a linear tape curve is derived.

An example of a more complex target shape is shown in Fig. 12. With its curved geometry, the target shape consists of a multitude of triangles. In the pre-process, the triangle centre points are projected into the plane of the trendline. Fig. 11 shows the projection points (blue) and the smoothed Savitzky-Golay filter curve (red).

Due to the curved geometry, the averaged normal vector is causing an inclination of the projection plane, which leads to a non-optimal starting solution (Fig. 12a), since the tape is inclined as well. However, the evolutionary algorithm allows a rotation of the tape by varying the rotation angles α_i (Fig. 12b). Thanks to the evolutionary algorithm, the optimization process still develops a near net shape tape geometry.

The pre-process as well as the evolutionary algorithm have multiple settings which allow a fine tuning of the optimization. For the pre-process, these are mainly the coefficients of the Savitzky-Golay filter and the maximum distance of the linear tape curve to the smoothing curve. For the evolutionary algorithm, a multitude of settings can be selected for selection, crossover and mutation method as well as population size and number of generations. Research on the effect of these parameters will be conducted in future work.
With the settings which are presented above, the evolutionary algorithm functions rather as local optimizer than as a global searching algorithm. Yet, since the starting solutions from the pre-process already have a very high fitness, a local search near the starting parameters is sufficient. However, in case the pre-process is not able to find good starting solutions, the optimization can still be performed by using a random initialization and genetic functions and settings which focus more on a global search.

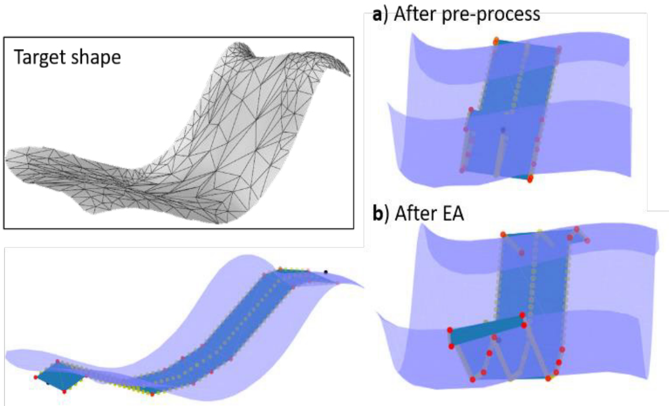

Fig. 12. The tape can fit to the shape of a complex curved geometry

4. Summary and Outlook

An Approach for the bending parameter optimization of the UD-Tape has been implemented. It is based on an analytical pre-process and evolutionary optimization of the final parameter set. It is able to derive parameter sets for complex component shapes in a short calculation time (few minutes). However, it requires a careful selection of optimization parameters (e.g. parameters of the pre-processing, generation size, crossover rate). Therefore, the influence of the parameters will be analyzed and the mobility of bends shall be improved. The influence of the parameters will be analyzed in order to improve the selection and automate the parameter selection. Although the functionality of analytic preprocessor and evolutionary optimization was shown, there are some changes to be made. The mobility of bends will be improved by changes in the chromosome description to avoid running into local optima when using random initial values or to decrease the influence of bend positions determined by pre-processing. This way, the evolutionary algorithm shall be used more as a global optimizer instead of a local optimizer. To demonstrate the process chain, a combined digital-physical process chain will be implemented which produces prototype reinforcements based on the optimization result on the fly.

Acknowledgement

The research documented in this manuscript has been funded by the German Research Foundation (DFG) within the International Research Training Group “Integrated engineering of continuous-discontinuous long fiber reinforced polymer structures“ (GRK 2078). The support by the German Research Foundation (DFG) is gratefully acknowledged.

References

[1] Hirsch, J., 2011. Aluminium in Innovative Light-Weight Car Design. Materials Transactions *52*, p. 818.
[2] Bücheler, D., 2017. *Locally Continuous-fiber Reinforced Sheet Molding Compound*, Karlsruhe.
[3] Coutandin, S., Brandt, D., Heinemann, P., Ruhland, P., Fleischer, J., 2018. Influence of punch sequence and prediction of wrinkling in textile forming with a multi-punch tool. Production Engineering *1*, p. 5.
[4] Angerer, A., Ehinger, C., Hoffman, A., Reif, W., Reihart, G., 2011. Design of an Automation System for Preforming Processes in Aerospace Industries. IEEE.
[5] Kunz, H., Raatz, A., Dilger, K., Dietrich, F., Schnurr, R., Dröder, K., 2013. Form-flexible Handling Technology for Automated Preforming. ICCM19 *2013*.
[6] Brecher, C., Emonts, M., Ozolin, B., Schares, R., 2013. Handling of Preforms and Prepregs for Mass Production of Composites. ICCM19.
[7] Bruns, C., Raatz, A., 2017. Simultaneous Grasping and Heating Technology for Automated Handling and Preforming of Continuous Fiber Reinforced Thermoplastics. Procedia CIRP *66*, p. 119.
[8] Kordi, M.T., Hüsing, M., Corves, B., 2007. Development of a Multifunctional Robot Endeffector System for Automated Manufacture of Textile Preforms. IEEE.
[9] Förster, F., Ballier, F., Coutandin, S., Defranceski, A., Fleischer, J., 2017. Manufacturing of Textile Preforms with an Intelligent Draping and Gripping System. Procedia CIRP *66*, p. 39.
[10] Kupzik, D. Flexible preforming of CFRP by robot based bending. https://youtu.be/HjTxdq9gwqM. Accessed 2 May 2019.
[11] Fengler, B., Kärger, L., Henning, F., Hrymak, A., 2018. Multi-Objective Patch Optimization with Integrated Kinematic Draping Simulation for Continuous–Discontinuous Fiber-Reinforced Composite Structures. Journal of Composites Science *2*, p. 22.
[12] Belongie, S., Weisstein & W, E. Rodrigues' Rotation Formula. http://mathworld.wolfram.com/RodriguesRotationFormula.html. Accessed 22 March 2019.
[13] Anyfantis, K., Foteinopoulos, P., Stavropoulos, P., 2017. Design for Manufacturing of Multi-material Mechanical Parts: A Computational Based Approach. Procedia CIRP *66*, p. 22.
[14] Schwennen, J., Kalbhenn, L., Klipfel, J., Pfeifle, J., Kupzik, D., Fleischer, J., 2018. Evolutionary Optimization of the Failure Behavior of Load Introduction Elements Integrated During FRP Sandwich Structure Manufacturing. Procedia CIRP *67*, p. 410.
[15] Goodman-Wilson, D. Galileo: a Distributed Genetic Algorithm. https://github.com/DEGoodmanWilson/Galileo. Accessed 12 April 2019.
[16] Savitzky, A., Golay, M.J.E., 1964. Smoothing and Differentiation of Data by Simplified Least Squares Procedures. Analytical Chemistry *36*, p. 1627.