



Research Article

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Continuous Orbital Winding of Thermoplastic FRPs

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Abstract

Today's markets are characterized by a strong need for automation in the thermoplastic FRP component production. Therefore, as part of the federal excellence cluster "MERGE multifunctional lightweight structures" the development of a novel processing method was realized, which is a synthesis of thermoplastic tape winding and automated tape placement technology. The new continuous orbital winding (COW) process, based on a modular technology concept with various processing units, enables the production of closed structural components and allows the direct combination with upstream and downstream processes. Hence a value chain improvement can be reached. That is achieved by linear motion of the winding mandrel (e.g. thermoplastic liner) along its longitudinal axis through the rotating winding units. The winding units coat the liner with unidirectional reinforced thermoplastic semi-finished structures by the use of tape placement devices. The applied thermoplastic tape welding process merges the matrix material of the incoming thermoplastic tape and the one of the previous layers.

This paper is presenting the validation of the manufacturing process of closed structural rotational and non-rotationally symmetric component using unidirectional fiber reinforced tapes, with the pilot plant for COW technology. In the first step of implementing a new part, the dataset of the part model is converted into a triangulated surface model in .stl file format. Following, the model can be imported into a Mathcad® file to project the winding pathway on the surface. These trajectories are used to calculate and determine the drive parameters by an inverse kinematic algorithm. Subsequently, the pilot plant can wind the profile with the computed contour. The final evaluation of the welding quality is necessary for the validation of the manufacturing process.

Keywords: Fiber reinforced thermoplastic tape; Winding process; Tape placement; Orbital winding/wrapping process; Mass production process; Automatic trajectory generation

Introduction

In order to satisfy the requirements of functionality and energy and material efficiency, the reduction of moving masses in transportation systems (e.g. cars, trains, electric vehicles) is of crucial importance. The comparatively low masses, high specific strength and the opportunity for large-scale production of fiber-reinforced thermoplastics are showing great potential for industrial applications. One part of the federal cluster of excellence MERGE Exc1075 "technology fusion for multifunctional lightweight structures", was focusing on the development of the novel

technological concepts. As a result, a technology for continuous generation of structural components with convex or concave surfaces was realized by applying an inverted winding process. For the validation of this technology, a pilot plant was developed and tested. The layer structure is realized by welding the fiber reinforced thermoplastic tapes and pressed on with defined pressure onto the closed winding core. The mandrel is linearly guided through the rotating winding units and can be made of metal as durable mold or made of thermoplastic, which remains in the structural component. Possible mandrel geometries are shown in Figure 1 (rel. [1,3,4]).



Figure 1: Exemplary structural components for orbital winding technology, rel. [1,3,4].

The key objective of the present research and development activities is the process automation by automated trajectory generation of driving parameters for each orbital winding unit, which is necessary for the implementation. This preprocessor is using directly the 3D dataset provided by the CAD system. The import of the STL-dataset (ASCII Format) is realized with Mathcad interface. Next, the data preparation is performed, and a curved pathway is calculated. The guide ways are computed, and the machine datasets derived by the use of an algorithm for movement kinematics [1]. The validation of the developed software tool for the orbital winding process is conducted at the pilot plant.

State of the Art

The novel process is a combination of thermoplastic automated tape laying (ATL) and automated tape winding (ATW) technology. Both processes are mainly using unidirectional fiber reinforced thermoplastic tapes. The layer structure is realized by the melting and depositing of the thermoplastic tape. The layers are fused by locally melting the matrix material with convective heat transfer (hotgas) or radiation (IR radiation or diode laser). The tapes are supplied on spools with a width of up to 300 mm and a thickness in the range of 0.12 mm to 1 mm [2].

Thermoplastic tape winding

The fiber-reinforced tape is pulled off from the coil by the rotation of the winding core and molten in front of the deposit position. The tape tension and the resulting retraction force in the tape are used to apply consolidation pressure in the contact area between layers, thus fusing the winding layers on each other. The winding process is used to produce rotationally symmetrical closed bodies [2].

Thermoplastic tape placement

A multi-axis system with a tape placement head is used for direction variable placement of the usually unidirectional fiber-reinforced tapes. The tape placement is typically realized on

planar or curved tools by applying heat for the melting of the tape material and pressure for consolidation. This process is used to produce large components or to implement local thickenings as well as reinforcements, usually designed to be functional and load appropriate. The tape material is conveyed by the relative movement of the laying unit to the tool surface or by driven feed rollers. The tape is heated up to melt temperature before it reaches the drop-off point and is consolidated with the required compaction force of the pressing unit [2].

Continuous orbital winding (COW)

The aim of the orbital winding process is to go beyond the state of classical winding of rotational symmetrical profiles to generate variable cross-sectional profiles. Pre- and downstream technologies are taken into account for integration into large-scale production concepts and to implement a higher level of value-added chains. For this purpose, a modular process chain was developed, shown in Figure 2. The structure of the continuous orbital winding technology also accounts for further processes, e.g. for functionalization or integration of auxiliary components in the layer structure [3-5].

The winding concept is derived from an inverted winding principle. Contrary to the conventional winding principle, the application unit is rotating around the winding mandrel. The winding mandrel is solely driven in axial direction.

A special kinematic system was developed for the orbiting motion of the application unit around the local profile cross-section. It allows the compaction roller to freely follow even complex geometries. The basic design of the multi-axis system developed for this purpose (Figure 3) features a radial and a tangential actuator to follow the contour as well as a tilting capability to adapt to the local surface.

The functional principle was validated with the realization of a modular structured pilot plant. The key components are the

winding units (Figure 4) which have been specifically developed on the basis of the operating principle (Figures 2 & 3). The identical

design of the winding units allows for a modular construction in series (Figure 5).

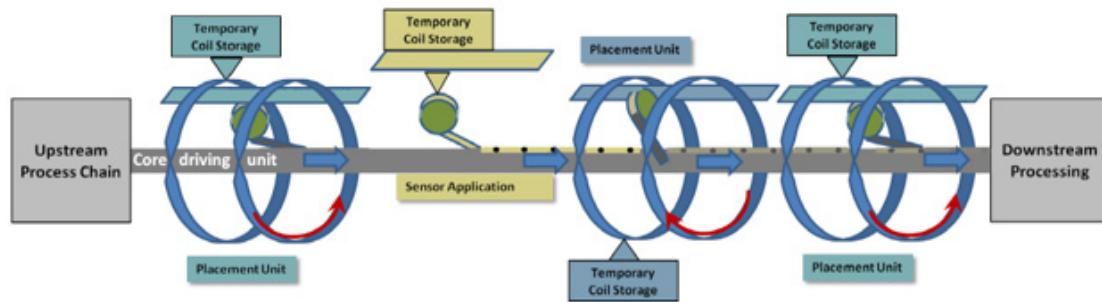


Figure 2: Concept of process chain for Continuous Orbital Winding Technology [6].

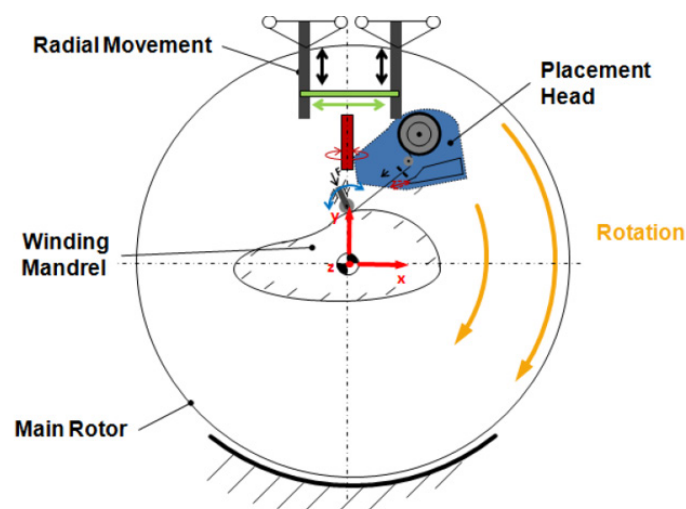


Figure 3: Movement of the tape placement unit around a cross-section profile [4].

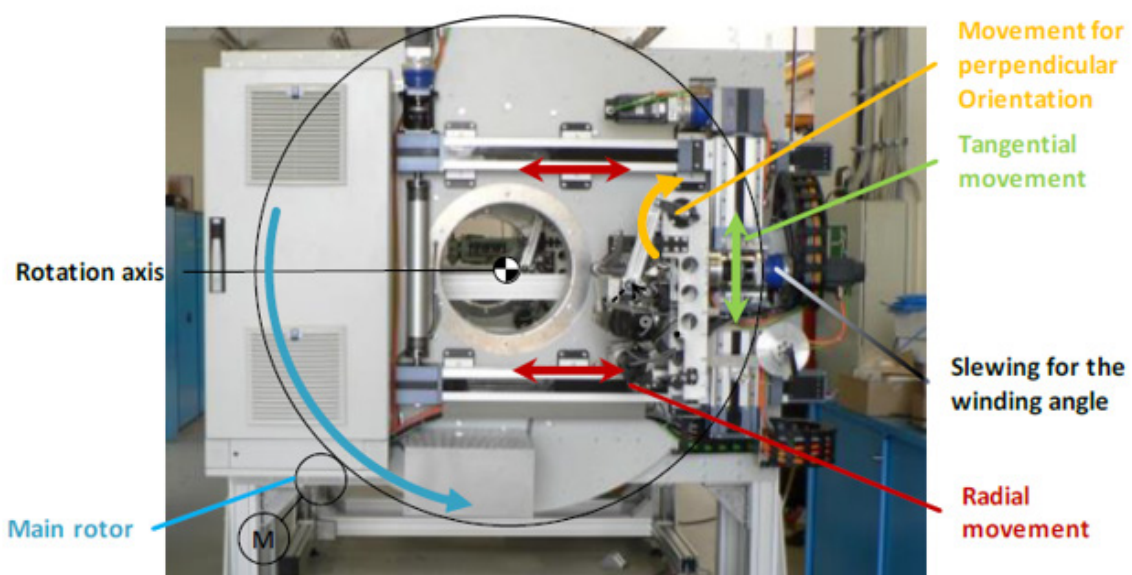


Figure 4: Assembly of a winding unit and direction of movement of the axis system, rel. [6].

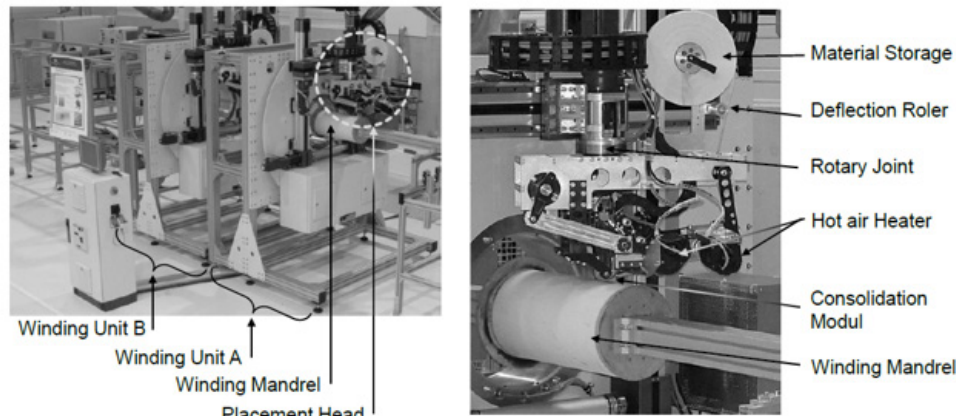


Figure 5: Orbital winding system and orbital placement head, rel. [6].

Methods

In the case of in-line orbital winding, unidirectional fiber reinforced or also bi-axial prepreps can be processed into rotationally symmetric (cylindrical parts) and nonsymmetric near-net-shape structures and complex structural components. For this application, the present article describes the functionality of an adequate offline machine control as preprocessor and simulative functionality tests in the multibody mechanism tool in the CAD-system Pro-Engineer.

Control of the winding process and calculation of the trajectory

For the automated control of the machine system and process monitoring it is necessary to automate an

upstream motion control system. The aim was to use the CAD

based component contour. The resolution of this task is preceded by the development of a formalism, which includes the following essential steps:

- Creation/Development of a CAD-based STL-file in ASCII format with a sufficiently accurate resolution → Creation/Designing a surface model
- Mathcad interface for reading the data and creation of the surface model derivation of the triangulated surfaces
- Design of the winding path as the guide way
- Illustration of the kinematic model in the Mathcad
- Implementation of the inversion of the inverse kinematics to compute the drive data sets in order to follow the winding path.

```
solid KERNKONTUR_INNOVATIV
facet normal 9.998306e-01 0.000000e+00 1.840346e-02
outer loop
vertex 1.998645e+02 1.100000e+03 7.360136e+00
vertex 2.000000e+02 8.500000e+02 -6.123234e-21
vertex 2.000000e+02 1.100000e+03 -6.123234e-21
endloop
endfacet
...
facet normal -9.173575e-01 1.647722e-02 -3.977231e-01
outer loop
vertex -1.720716e+02 7.127811e+02 -1.070147e+02
vertex -1.712464e+02 7.127811e+02 -1.089180e+02
vertex -1.730310e+02 5.751410e+02 -1.105041e+02
endloop
endfacet
endsolid KERNKONTUR_INNOVATIV
```

Figure 6: Sample code from an ASCII formatted STL file, rel. [5].

The detailed procedure for data preparation: and determination of drive parameters is described below STL File-Import The data set in a stl component model describes the shape of the component surface with triangular areas or facets. For each surface element three vertices are assigned, and a normal direction is defined by a vector. The latter determines the material side and the outside of the part as well. The specification of the corner points and the normal vector results from three coordinates relative to the defined reference coordinate system. For the formalism to treat the data, the ASCII variant of the STL format is used (Figure 6), which

can be generated and read by almost all commercial CAD systems. In the next section the treatment of the triangular geometry and the path planning will be described. Both steps were performed using the PTC Mathcad calculation software.

The requirements for the STL in ASCII format of the winding profile are specifically defined. For example, the imported reference coordinate system must correspond to the machine system. The component longitudinal axis is described by the y-axis of the coordinate system. The CAD part, the stl-format and the imported model are shown in Figure 7.

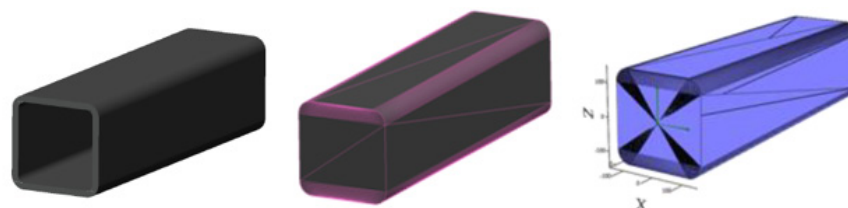


Figure 7: Steps for the import of the STL-file in Mathcad.

Calculation of the path: After Data import of the point and vector coordinates grouped into triangles, a scan of the complete triangle mesh is performed. Figure 8 shows the contact curve that

arises when the consolidation roller is driven once completely over a constantly shaped winding core [1]. Here, the slope of the curve corresponds to an uninterrupted winding of the tape (Figure 8).

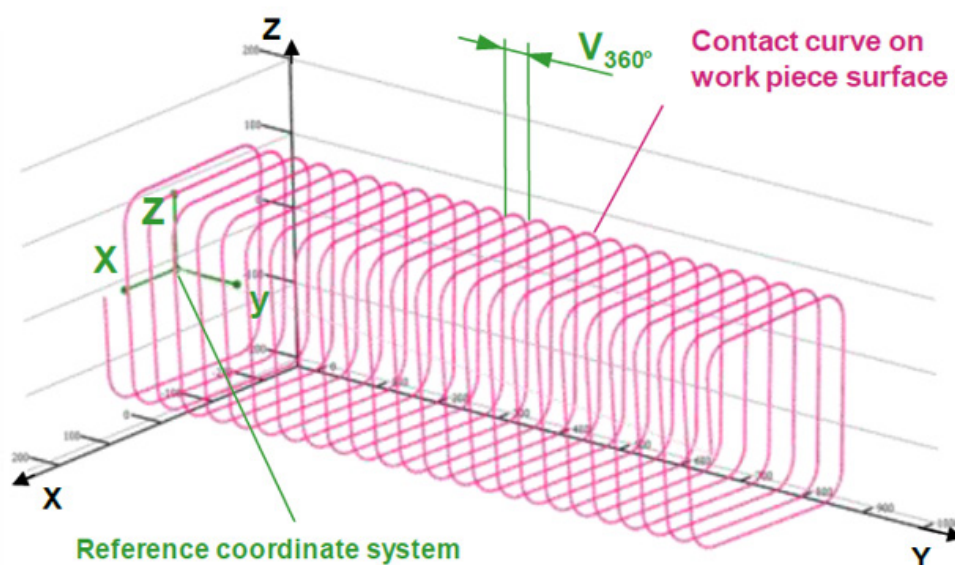


Figure 8: Contact curve of the roller on the surface of the winding mandrel, rel. [5].

The feed of the core per revolution of the laying head equals the actual width of the tape, reduced by twice the amount of overlap.

- Curve ascends helically along the longitudinal axis of the winding mandrel

- Calculation of the intersections → equidistant on the work piece surface

Design of the Guide Way

$$V_{360^\circ} = B - 2u \quad (1)$$

The calculation of the contour points P_i takes place by means

of an intersection calculation between the triangular surface and an ascending ray performing a screw motion. As the ray displaces a unit of length ΔV in

the Y direction (looking at Figure 7), its direction (initially parallel to the X axis) rotates about the Y axis with the angular step Δ_φ . The constant ratio

$$Q = \frac{\Delta_v}{\Delta_\varphi} \quad (2)$$

can be interpreted as the screw pitch.

The intersection calculation is performed for each triangle until the current triangle of the surface is found. In the next step, the cutting problem between plane and line has to be solved. Multiple solutions are eliminated by considering the positive beam direction and the boundaries of the triangles.

With regard to the later integration into the control, there was the additional requirement to distribute the points equally spaced on the core surface. This is achieved numerically up to the accuracy ε by first estimating the angular step Δ_φ

$$\Delta_\varphi \approx \frac{\Delta_L}{\rho} \quad \text{with } \rho \dots \text{radius of curvature of the contour} \quad (3)$$

for a fixed increment ΔL on the contour. Then, by sampling the triangles, the intersection P_i is calculated and the difference to the previous contour point P_{i-1} is compared with Δ_L . Using Newton's method, the correct amount Δ_φ is now iteratively calculated and stored in a first list with n rows.

After scanning the profile, the consumption length of the tape can be approximated using the following equation

$$L = \sum_i |P_{i+1} - P_i| \quad \text{für } i=1, \dots, n-1 \quad (4)$$

The deviation from the actual length is less than 0.1% and is neglected due to the elasticity of the material. The

spatial curve itself can now be examined in particular for its curvature behavior, since, for example, falling below the roller radius in the case of concave sections can lead to impacts and connection errors [1,6].

Choice of winding angle: In addition to the laying strategy described above, other variants are possible. Beyond from the tape laying with overlap area, a free winding angle of the tape with feeds $V_{360^\circ} > B$ can be selected, since the corresponding movement possibilities are provided for the laying unit. This is important, if different winding angles are to be modeled during the production program.

Motion control

Determination of the drive position: The result of the previous chapter's calculation is a coordinate list of the points P_i consisting

of equally spaced points of the contact curve of the roller center on the winding mandrel surface. This coordinate list is supplemented by associated infeed positions V_i of the winding mandrel and the angular position HZ_i of the main rotor. The following describes the inclusion of this curve in the machine concept for motion control.

First, the points

$$R_i = \begin{bmatrix} {}^xRMB \\ {}^yRMB \\ {}^zRMB \end{bmatrix} = P_i + r \cdot K_i \quad \text{with } r \dots \text{radius of the roller} \quad (5)$$

of the roller center path are calculated from contour (roller center path R_i). It can be imagined that a vector of

length r is added to the contact point P_i in the direction of contour normal

$$K_i = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ -1 & 0 & 0 \end{bmatrix} \frac{P_{i+1} - P_i}{|P_{i+1} - P_i|} \quad (6)$$

To estimate the curve normal, the tangent direction is calculated numerically and rotated by the specified rotational matrix by 90° around the longitudinal axis of the winding core (y-axis). The mechatronic axes shown in Figure 4 – have to be positioned in such a manner, that the roller takes the calculated position R_i at the end of the kinematic chain.

For this purpose, the inverse kinematics function

$$q = ik(x) \quad \text{mit } x = \begin{bmatrix} {}^xRMB & {}^yRMB & {}^zRMB & \beta \end{bmatrix}^T \quad (7)$$

$$q = [HR \ RZ \ TZ \ \alpha \ \theta]^T$$

for the backwards transformation of the position coordinates x of the roller into the axis coordinates q of the drives was created. It should be noted that the angular position of the main rotor HR changes uniformly (constant speed) and is thus already fixed.

Integration in the motion control: The diagrams in Figure 9 show typical axis positions during the revolution for a reference profile – the result of the inverse kinematics function Eq. (7). The diagram of the perpendicular orientation shows the limitation of the slewing angle at the consolidation mechanism in the range between $-45^\circ \leq \theta \leq 45^\circ$.

The drives are controlled by a master-slave coupling of all single-axis drives to a common master by 'electronic cam function'. As a first implementation, the infeed of the winding mandrel V to the master axis was determined

all diagrams in Figure 9 refer to V in the abscissa. Alternatively, it is envisaged to use the length of the contact contour as a secondary virtual master for the process control. This would have the decisive advantage in terms of process control, as it is possible to directly calculate the already used strip length and to control the laying speed of the tape as a motion control axis. In the course of the

determination of the characteristic curve in the laying process, this will be a decisive step to eliminate all nonlinearities on the laying

process by means of software, which are caused on the one hand by the kinematics and on the other hand by the core contour.

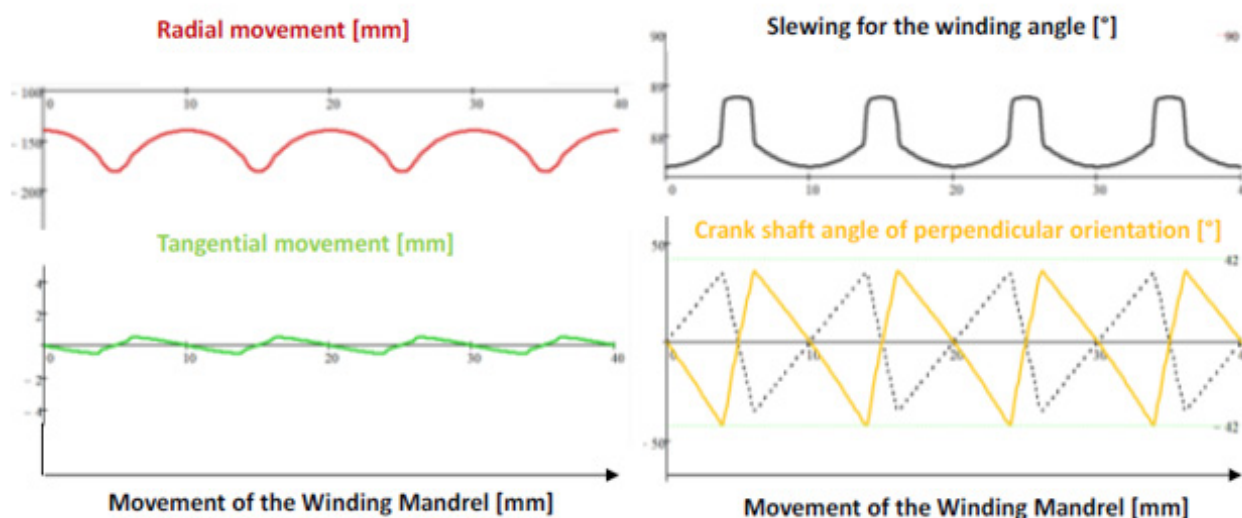


Figure 9: Graphs of the axis positions for a round around the shown rectangular profile.

Simulative tests: The generated drive data should be tested on the multibody simulation model in prior to the data transfer into the machine control of the pilot plant. For this purpose, the respective parameters of the drive axes are exported directly as several .grt files from the preprocessor and imported into the multi body system. With the subsequent kinematic simulation, both the

general movement and the movement along the trajectory are checked. Characteristic parameters of the higher-order motion functions are examined as well. Figure 10 shows significant positions of the movement of the MBS model during the simulation of the orbital motion.

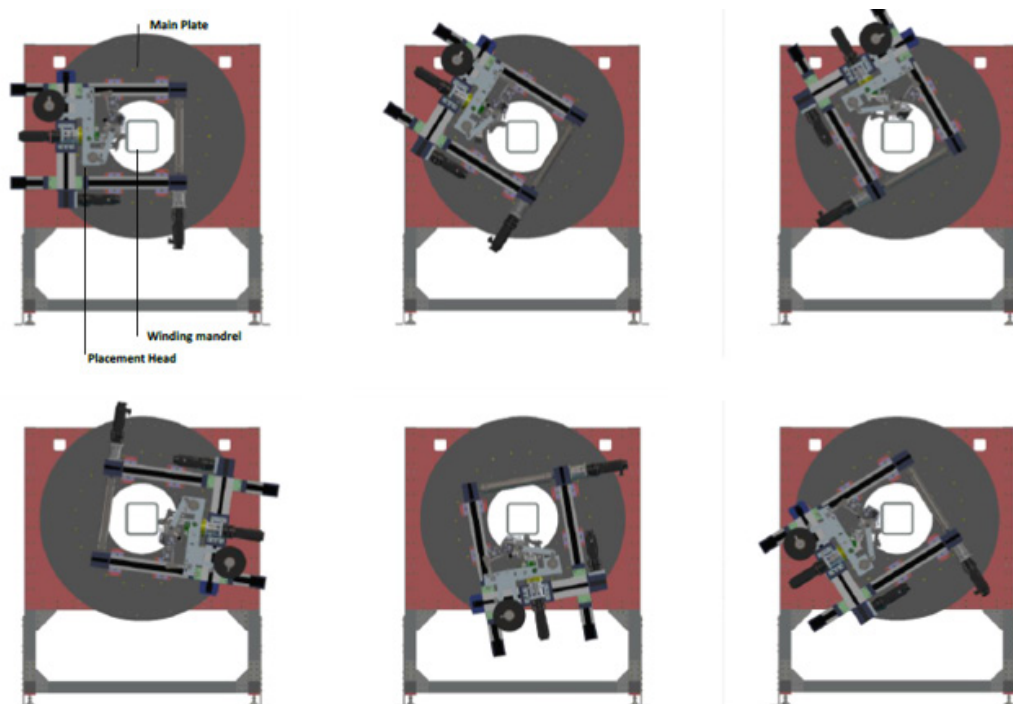


Figure 10: Several positions during the multi body simulation.

For the shown CAD model, the contour of the winding core was integrated in order to be able to perform a collision check in addition to checking the consistency of the drive parameters.

Validation of the COW Process

Preparation of experimental procedure

For the process, validation of the COW technology and the drive parameters determined by the preprocessor, a permanent mold for the winding mandrel was developed (Figure 11). This was modularly designed using a frame construction (similar to aircraft construction), later manufactured and assembled from sheet

metal and plates. This design allows the demolding of the wound structural component. For the appropriate handling within the pilot plant system, the winding mandrel was set on an aluminum carrier with dimensions $100 \times 100 \text{ mm}^2$, which is necessary for positioning and guiding of the core passage. The essential cross-section dimensions of the core contour are shown in Figure 11. The predetermined shape was designed in a way, that the mechanical properties can also be obtained from test specimen in order to verify the process. For the demonstration of the winding process of cylindrical parts the TAHYA liner for a CPV was used.

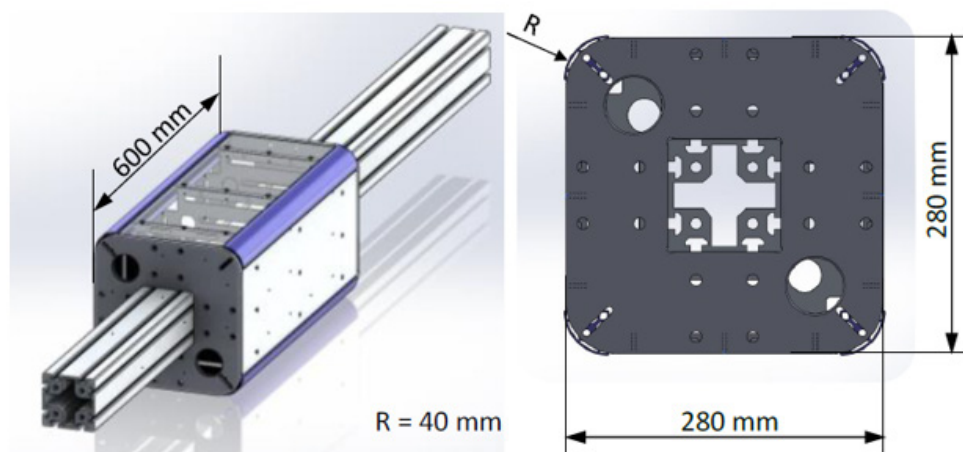


Figure 11: Winding mandrel using a frame construction for the validation of drives and the technology.

Experimental Procedure

At the beginning of the research program, the driving parameters were tested and validated with the real mechatronic system during the initial operations. Therefore, the datasets for the movement, generated from the 3D-part (see 3.1), were saved in the excel xls-format and imported into the machine control system via Ethernet interface. In the next step, the drive parameters were assessed by traversing the contour in set-up mode and then tested with the winding mandrel installed.

After the successful initial operations, feasibility studies were carried out regarding the processing of PP-GF 60 tapes for the square profile and the PA6-GF and PA6-CF tapes for the cylindrical parts, which were applied in a single layer without gaps. In the following layer, the deposition was overlapping with half tape width. For carrying out the experiments for validation of the process, the winding core was tempered in a temperature range of $90^\circ \text{C} \dots 110^\circ \text{C}$. In addition, the following essential parameters have been applied for the tape placement:

- Placement speed: ca. 1,5 ... 6 m/min
- Consolidation force: 120 ... 160 N
- Hot air temperature: $350 \dots 480^\circ \text{C}$ IR-Heater $8 \times 100 \dots 800 \text{W}$

- Tape width: up to 40 mm.

In this case, it can be shown that the determined drive parameters can be processed, and the characteristic processing map of the machine can be studied. In particular, the thermal process management in conjunction with the installation speed and the contact pressure of the tape deserves further and special attention. After successful processing and specification of the required core temperature, feasibility studies were carried out to process the FRPs.

For processing, parameters had to be adjusted, for example, for the energy input (deposition speed or hot air temperature) in order to melt thicker tape (tape thickness up to 0.4 mm) for the welding process.

The studies show that there is not enough heating power for processing. In a further step within the COW-Pilot plant was improved and optimized for the winding process of CPVs within the Horizon 2020 project TAHYA.

Therefore, the hot air heating system was replaced by an IR-Heating system (shown in Figure 1 and Figure 12 right). In addition, the liner guidance was new designed and installed in order to be able to wind liners with a length up to 5 m.

Results, evaluation and discussion

The wound structural parts were left on the winding mandrel for cooling after the winding process and then removed from the mold. At visual inspection it was seen that the layers at component's ends have not been completely consolidated. This can be explained

by the stabilization of the process parameters at the beginning of the laying process. The components obtained after trimming off the ends are shown in Figure 13. The specimens have the contour of the shape of the winding core. This provides the verification of the closed technology chain at the pilot stage.

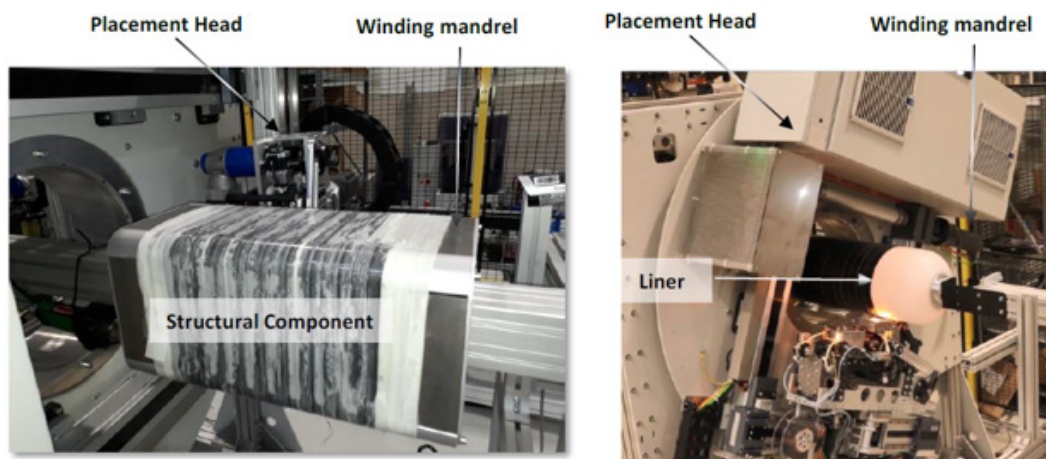


Figure 12: Studies of processing on different materials and profiles.



Figure 13: Structural parts from feasibility studies (left square profile, right cylindrical component).

The knowledge of processing speed, temperature regime and contact force technology map may enable strategies to dynamically control them based on the position of the roller on the core perimeter.

Summary and Outlook

The present work deals with the extension of the already developed and researched technological principle of orbital winding and the associated installed system. The aim is to provide the closed development chain from the designed structural component over the conversion into a surface model up to the machine control and finished part. In addition, the aim is to study simulate the values determined simulatively in the CAD system and with the pilot plant system. For this, an automated calculation tool was developed for orbital winding, which uses the generic component geometry of the wound body. This is a kind of pre-processor for automated system control, which generates the winding path on the surface based on the CAD data and derives the drive parameters of the

individual actuators for the kinematic system. The determined drive parameters are tested on the machine system of the pilot plant and validated together with the process technology during the production of test specimens.

First of all, standard commercial unidirectional fiber-reinforced tapes were processed tape was studied. The processing of unidirectional was successfully accomplished. The determined data records are thus classified as sufficiently accurate for the processing process. Finally, knowing the technology map of processing speed, temperature regime, and contact force will also allow strategies to dynamically control them based on the position of the roller on the core circumference.

Furthermore, previous limitations to the shape of the winding core are to be eliminated- so the stl processing with profiles of variable cross section axis coordinates can be realized. It is planned to test the implementation on the machine, as an online change of the electronic cam must be carried out after each revolution.

Acknowledgement

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Conflict of Interest

No conflict of interest.

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