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Study on the validation of ring filament winding methods for unidirectional preform ply manufacturing

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Abstract Ring filament winding enables processing of continuous fibers for manufacturing unidirectional non-crimp unidirectional preform plies on straight-, curved-, or closed-mandrel geometries. However, unidirectional processing of tows can lead to increased lateral tow slippage. The objective of the present study is thus to validate unidirectional winding methods for ring filament winding, performing geodesic and non-geodesic trajectories analytically and experimentally. Implementation of geodesic paths investigates the influence of the tensile force and take-up velocity on the winding angle reproducibility. Non-geodesic winding paths are conducted here dependent on winding methods, slippage coefficients, and the mandrel’s surface materials, evidencing the occurrence of lateral tow slippage by measurements of nip-point forces. Findings indicate an excellent reproducibility of geodesic paths independent of the process velocity. Non-geodesic paths were partially validated because of the occurrence of lateral tape-slippage and a tape side-inclination effect, correlating an increased stick behavior to higher local normal pressure.

Keywords Filament winding, friction coefficient, preform, carbon fibers, geodesic, non-geodesic, slippage coefficient, unidirectional

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Introduction Filament winding is a state of the art manufacturing technology for the production of straight-formed composite parts (e.g. profiled beams, pressure vessels¹⁵–¹⁶ or isogrids/⁶ truss structures). High material-deposition rates plus the possibility to process thermoset and thermoplastic matrix systems are typical advantages ensuring process profitability.⁷–¹¹ In addition, the direct adjustment of the tow tensile-force contributes to component quality.¹²–¹⁶ The development of a four-axis machine configuration, equipped with a multiple-head deposition system, highlights an advanced manufacturing milestone for increasing productivity.¹⁷–¹⁹ However, the winding principle, consisting of a continuous mandrel rotation combined with a feed motion of the tow deposition unit along its longitudinal axis, remained the same. A full winding pattern consequently consists of a single self-intersecting tow trajectory, which systematically repeats, winding filament flush to itself, after every mandrel rotation.¹⁵,²⁰,²¹ Due to undulations, tow self-intersections are not only related to pattern’s lower lay-up accuracy²² but also to the laminate’s loss of strength.²³–²⁶ Another process constraint restricting further applications is the machine complexity required to process a limited variety of mandrel shapes.

The aim of the ring filament winding technique is to solve these constraints. The process consists of a ring-shaped configuration of the fiber deposition unit, composed of at least one bobbin carrier, a tow guidance system, and a deposition head (Fig. 1(A)).

The winding motion is performed through the continuous winding ring rotation. A customization of winding angles is achieved by coupling the winding ring or the mandrel to a...
feed unit (e.g. a robotic arm). Such centralization of winding and feed motions into a single unit eliminates the typical necessary rotation of the mandrel around its longitudinal axis, permitting it to process continuous tows on straight-, curved-, or closed-shape mandrel geometries.

Aside from standard winding methods, ring filament winding also permits an adaption to manufacture preform plies with unidirectional fiber orientations illustrated in Fig. 2. The main difference between these methods is the pattern symmetry over profile circumference. While (angled-) hoop-winding patterns are symmetric over the mandrel’s profile, helical-winding patterns are asymmetric.

Ring filament winding (i.e. toroidal filament winding) was first investigated numerically by Zu et al. Further studies focused on the optimization of mandrel cross-section and the stability and design of freedom of geodesic and non-geodesic fiber trajectories for toroidal pressure vessels. Zu et al. outlined that non-geodesic fiber paths not only fulfilled geometric requirements for a whole unidirectional pattern, but also contributed to the toroidal vessel’s mass reduction, allowing optimal alignment of fiber paths along load directions. Schädel et al. studied ring filament winding numerically and experimentally as a novel joining method for space-frame T-Joint intersections.

**Objective**

The present study aims to validate unidirectional winding methods through the implementation of geodesic and non-geodesic fiber paths by ring filament winding at room temperature. First, the influence of the winding ring configuration on the tow tensile force amplitude/magnitude is determined. Then, the influence of parameters (i.e. tensile force, take-up velocity, winding method, slippage coefficient, and mandrel surface material) on the reproducibility of winding paths is investigated. The measurement of process forces at the nip-point should indicate the occurrence of tow side slippage. General goals of this paper are to determine key parameters for further process development and identify factors causing deviations.

**Analytics of geodesic and non-geodesic trajectories**

During filament winding a continuous tow is subjected to a tensile force $F_t$ parallel to the fibers orientation. At the nip-point, $F_t$ is then split up into five force vectors (Fig. 1(B)). Each force vector magnitude and direction are determined by several process-specific parameters. Analytical investigation of local force ratios allows an advanced analysis of lateral tow slippage tendencies, indicating consequently relevant parametrical scopes for experimental verification.

**Geodesic trajectories**

Geodesic trajectories are the shortest link between two reference points on a surface. According to the law of Clairaut, geodesics characterize stable trajectories with a geodesic curvature $\kappa_G$ equal to zero. Regarding the filament winding process, this means that there are no tow lateral forces influencing the fiber trajectory.

Specifically for a cylindrical straight mandrel, geodesic winding paths are designed by the angle-dependent tow...
take-up velocity $v_t$. The take-up velocity is thus the resultant cross-vector of combining the winding ring revolutions $n_0$ with the feed velocity of the mandrel $v_f$ for a given winding angle $\alpha$ (Equation (1)).

$$v_t(\alpha) = \sqrt{n_0^2 + v_f^2} = n_0 \cdot \sqrt{1 + \left(\frac{\tan \alpha}{\alpha}\right)^2}$$  

(1)

Fig. 3(A) illustrates the progress of the normal force for geodesic winding paths at the nip-point, dependent on winding angle and tensile force variance. A profile radius of 60 mm is hereby considered. The plotted surface outlines a sinusoidal decrease of $F_n$ with dropping winding angles. Its correlation with the tensile forces suggests a higher susceptibility of trajectory deviation as tensile force fluctuations increase.

**Non-geodesic trajectories**

Non-geodesic trajectories are characterized by their geodesic curvature being unequal to zero. In the case of a cylindrical straight mandrel, the Liouville expression for the geodesic curvature $\kappa_G$ is given by the ratio of winding angle $\alpha$ and the path length between two discretization units (Equation (2)).

$$\kappa_G = \frac{\Delta \alpha}{\Delta s} = \frac{(\alpha_{i+1} - \alpha_i)}{(s_{i+1} - s_i)}$$  

(2)

According to Euler,32 the normal curvature $\kappa_n$ is dependent on the winding angle and mandrel profile radius $r_m$ (Equation (3)).

$$\kappa_n = \frac{(\sin \alpha_i)^2}{r_m}$$  

(3)

As a mathematical variable for designing non-geodesic winding paths, the slippage coefficient $\lambda$ is specified as the ratio between the geodesic and the normal curvature25,26 according to Equation (4)

$$\lambda = \frac{F_s}{F_n} = \frac{\kappa_G}{\kappa_n}$$  

(4)
expressed in terms of Coulomb (Equation (8)) is appropriate,\textsuperscript{35} where $k$ is the friction constant and $n$ is a fitting parameter related to material deformation.

\[
\mu_s = k(F_n)^{n-1} \tag{8}
\]

The governing condition for the absence of lateral tow slippage for non-geodesic winding paths is set by the inequality $\lambda < \mu_s$.\textsuperscript{25} Fig. 3(B) illustrates the increasing sensitivity of lateral tow slippage toward decreasing winding angles, indicating an intensification of this tendency by setting higher geodesic curvature levels. In the present investigations, Amonton–Coulomb friction is assumed.

Experiments

Ring filament winding setup

The ring filament winding setup consists of a six-axis robotic arm with an integrated force-torque sensor, an asynchronous electric motor-actuated winding ring, and a straight cylindrical mandrel (Fig. 4).

The robotic arm holds and positions the mandrel concentrically to the central-line axis of the winding ring,
Materials

For experimental validation, a carbon-fiber tape was selected as winding material. The tape is manufactured with 410 tex linear weight tows, covered on each side with a 6 wt.-% co-polyamide thermoplastic fleece. The fleece’s application contributes to the tape’s width rigidity, keeping the preform areal weight nearly constant and avoiding preform gap formation by reduced form fluctuations. Additionally, it allows thermal conditioning of multiple ply preform lay-ups prior to infusion, functionalizing it as interlaminar toughening after consolidation.

The mandrel surface was prepared with two different textiles to investigate surface topography interaction with the processing carbon-fiber tapes. A surface covered with a polyester plain-weave peel-ply fabric is analogous to the mating material conditions of the first preform ply. The peel ply’s warp direction is hereby oriented longitudinally. Aiming to reproduce the materials interfacial conditions for following preform plies, a hoop-wound preform layer was prepared, orienting filaments circumferentially. Fig. 5 illustrates both material features programmable back and forth longitudinal accelerations. A straight cylindrical mandrel has been selected for all experiments, representing the simplest mandrel design and permitting an easy implementation of winding trajectories. The winding ring is set up with seven tow guidance elements, a bobbin carrier, and an attached hysteresis brake. Table 1 lists the settings of the winding ring configuration.

Table 1 Overview of the test-rig settings

| Description                  | Unit     | Specification            |
|------------------------------|----------|--------------------------|
| Mandrel diameter $\varnothing_{\text{mandrel}}$ (mm) | 120      |
| Wind. ring diameter $\varnothing_{\text{WR}}$ (inside; outside) (mm) | 345; 880 |
| Meas. frequency (Hz)         |          | 250                      |
| Bobbin hysteresis brake clutch (Nr.; $\varnothing_{\text{clutch}}$) |          |
| Wind. ring (-; mm)           |          | 4; 25                    |
| Dep. head (-; mm)            |          | 3; 12                    |

Table 2 Overview of physical characteristics of both selected interfacing materials

| Description                                      | Unit     | A                        | B                        |
|--------------------------------------------------|----------|--------------------------|--------------------------|
| Material                                         | (–)      | PAN carbon fiber         | Polyester plain weave peel ply fabric |
| Fiber type                                       | (–)      | IMS60                    | –                        |
| Weight linear$^a$; area$^b$ (tex$^a$; (g/m$^2$)$^b$) | 410      | 85                       |
| Filament orientation                             | (°)      | 0°                       | 0°/90°                   |
| Nr. of filaments                                 | (–)      | 12 k                     | 18.9                     |
| Filament diameter $\varnothing_{\text{fil}}$ (μm) | 5        | –                        | –                        |
| Filament density $\rho_{\text{fil}}$ (g/cm$^3$)  | 1.79     | –                        | –                        |
| Tape width $w_{\text{tape}}$ (mm)                | 5        | –                        | –                        |
| Coating type                                     | (–)      | Co-polyamide fleece      | –                        |
| Coating rel. weight ratio (%)                    | 2 × 6    | –                        | –                        |
| Fabric design (warp; weft)                       | (tow/cm) | 20.8; 30.6               | –                        |
| TOW width $w_{\text{weft}}$ (warp; weft) (μm)    | –        | 477.9; 281.5             | –                        |

Figure 5 Microscopy of both selected mandrel coverage materials for experimental validation: (A) polyester plain-weave peel-ply-fabric and (B) 12 k IM carbon-fiber tape coated with a co-polyamide thermoplastic fleece.
Applying the helical winding method, validation experiments of geodesic winding paths investigated the influence of the tow tensile force and take-up velocity on the reproducibility of winding angles. Fig. 6 illustrates the geodesic trajectory qualitatively. Winding angles were discretized from 15° to 85° to verify the non-linear normal force in accordance with analytics (Fig. 3(A)). A central composite design (CCD) was applied to perform the experiments. For this test sequence, the mandrels surface was tested only with the peel ply fabric coverage.

Non-geodesic winding paths were performed parameterizing the mandrels coverage material, the winding method, and the slippage coefficient magnitude. All other factors were kept constant in conformance to the central levels of the geodesic CCD-plan. To perform the respective experiments, a fractional surface conditions, while Table 2 summarizes their physical characteristics.

### Experimental procedure

The influence of the winding ring configuration on the tow tensile force amplitude was investigated in preliminary experiments. The determination of optimal configuration settings intended to smooth $F_t$ fluctuations, implying uniform amplitudes along all winding trajectories. Hence, tensile force measurements were performed online to the winding procedure, first altering the number of tow guidance elements or the weight distribution at the winding ring circumference (Table 3(A)). Further measurements characterized feasible $F_t$–scope as a function of $v_t$ for five hysteresis brake torque levels (Table 3(B)).

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**Table 3** Overview of the parameterization of preliminary experiments, investigating the tensile force amplitude/magnitude dependency from respective (A) winding ring settings or (B) hysteresis brake settings

| Parameter                  | Unit       | Levels                   |
|----------------------------|------------|--------------------------|
|                            |            | −2 | −1 | 0 | +1 | +2 |
| (A) Preliminary experiments: Winding ring settings |            |    |    |   |    |    |
| Nr. of guidance elements   | (−)        | 4  | 7  | 0 | 1  | 2  |
| Unbalancing mass $\Delta m$ | (kg)      | 0  | 1  | 0 | 1  | 2  |
| Repetitions                |            | 2  | 2  | 2 | 2  | 2  |
| (B) Preliminary experiments: Characterization of hysteresis brake settings |            |    |    |   |    |    |
| Nr. of guidance elements   | (−)        | 7  | 7  | 0 | 0  | 0  |
| Unbalancing mass $\Delta m$ | (kg)      | 0  | 0  | 0 | 0  | 0  |
| Hyst. brake torque $M_b$   | (%)        | 0  | 12.5 | 25 | 37.5 | 50  |
| Take-up velocity $v_t$     | (mm/s)     | 30 | 73.5 | 137.2 | 201 | 244.5 |
| Repetitions                |            | 3  | 3  | 3 | 3  | 3  |

**Table 4** Parameterization settings for (A) geodesic and (B) non-geodesic winding path validation experiments. The multiple parametric combinations related to each plan were performed according to Hinkelmann et al.

| Parameter                  | Unit                  | Levels                   |
|----------------------------|-----------------------|--------------------------|
|                            |                       | −1.682 | −1 | 0 | +1 | +1.682 |
| (A) Geodesic winding paths: DoE Central-Composite-Design (CCD) Matrix |           |    |    |   |    |    |
| $\alpha$                   | (°)                   | 15 | 29.1 | 50 | 70.9 | 85  |
| $F_t(\alpha)$              | (N)                  | 7  | 10.6 | 16 | 21.3 | 25  |
| $v_t$                      | (mm/s)               | 30 | 73.5 | 137.2 | 201 | 244.5 |
| Repetitions                |                      | 3  | 3  | 3 | 3  | 3  |
| (B) Non-geodesic winding paths: DoE Fractional-Factorial (FF) Matrix |           |    |    |   |    |    |
| Material                   | Plain weave polyester peel ply | – | 12 k IMS60 carbon fiber |
| WP-shape (Winding method)  | O-Shape (Angled-Hoop) | – | S-Shape (Helical) |
| $\lambda$                  | 0.3                  | – | 0.5 |
| $F_t(50°< \alpha < 90°)$   | (N)                 | – | 16–10.65 | – |
| $v_t(50°< \alpha < 90°)$   | (mm/s)             | – | 137.2–30 |
| Repetitions                |                      | 3  | 3  | 3 | 3  | 3  |
take-up velocity at the vertex point, where adjacent filament orientations are also nearly 90°.

An imprint of winding paths on the mandrel surface on transparent foil permitted the measurement of winding angles. A Matlab-algorithm was applied to convert respective trajectories into a six-order polynomial function. Scanning the foil instead of taking a picture reduced image distortion errors, restricting picture scaling tolerances to ±0.5 mm. Tape normal forces were then derived correlating the measured α– and α-values (Equation (6)). Lateral forces are consequently determined by calculating λ out of the path's curvatures (Equations (2–4)) and multiplying it with the respective $F_n$-values (Equation (5)).

Results and discussion

Influence of the winding ring configuration on the tow’s tensile force

Measurements of the circumferential $F_c$ and axial $F_a$ forces performed for a minimally guided tow length, implementing four

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Figure 7 Illustration of the implemented non-geodesic winding trajectory, as O- or S-shaped winding paths respectively

Figure 8 Comparison of a typical online response for circumferential force $F_c$ and axial force $F_a$ vectors, highlighting amplitude fluctuations with respect to a short- (4-Elements) and a long- (7-Elements) guided tow length. Respective average values are indicated by the dashed lines. The numbered elements on the winding ring drawing (right) distinguish the guiding sequence of each element in accordance with the tow length: (1–4)/4 and (1–7)/7.
guidance elements, exhibit long-periodic sinusoidal amplitude gradients over +168% (Fig. 8). These enormous amplitude fluctuations are attributed to the pullout tow-angle variance between the bobbin and the first guidance element. In order to eliminate those fluctuations, the numbers of guidance elements were increased to seven, reducing the pullout angle at the bobbin and increasing the tow length to 1050 mm. Measurements indicate that short-periodic, uniformly distributed force amplitudes are achievable considering the adjustment of the relative position of each guidance element to the bobbin. These findings additionally specify design constraints for tow guidance configuration of any other process involving continuous tows, especially those that do not use electronic tow tensile force control systems.

From a production perspective, the winding ring motion is constantly influenced by mass loss, due to tow consumption. Thus, the influence of ring mass distribution on $F_c$ and $F_a$ amplitude is investigated. Measurements of both process force vectors, with an even weight distribution around the winding ring, demonstrate a uniformly short-periodic amplitude

![Figure 9](image)

**Figure 9** Comparison of a typical online response for circumferential force $F_c$ and axial force $F_a$ vectors, highlighting amplitude fluctuations with respect to an uneven (Mass_uneven) and even (Mass_even) mass distribution over the winding ring circumference. Respective average values are indicated by the dashed lines. Note the position of the unbalancing mass at the outer perimeter of the winding ring, on the opposite side of the fiber bobbin, indicated by the drawing on the right.

![Figure 10](image)

**Figure 10** (A) Influence of the take-up velocity on the tensile force magnitude for five levels of the bobbin’s brake torque. (B) Winding ring revolutions $n_r$ as a function of the motor rotational velocity $n_m$ using a $(V–)$ belt gear transmission, plotted for $M_b = 0\%$ and $M_b = 25\%$. Continuous diagonal lines correspond to constant gear transmission ratios $i$. Filled areas represent the $(V–)$ belt over-slip scope and geodesic rotational velocity scope, respectively.
response (Fig. 9). In contrast, measurements with the fixation of a 1-kg dead-weight at the outer diameter of the winding ring show long-periodic amplitude fluctuations, leading to lower average tensile forces. These discrepancies are attributed to an uneven inertia of the winding ring, caused by circumferential over-slip of the gear transmission (V–) belt (Fig. 10(B)). Therefore, an even weight distribution on the winding ring, which is generally controllable, has to be regarded for following validation tests.

Establishing these optimal settings, a reduction of discrepancies and a mostly uniform $F_c/F_a$ amplitude along the tow’s length is implemented. Fig. 10(A) characterizes the limits of $F_t$ between 4.7 and 25 N, differentiating its scope to a five-level combination of the brake torque power from 0 to 50% and the take-up velocity from 30 to 244.5 mm/s. Results show an increase of the averaged tensile force with the take-up velocity at each brake torque level, associated with the tow’s pull out friction within response (Fig. 9). In contrast, measurements with the fixation of a 1-kg dead-weight at the outer diameter of the winding ring show long-periodic amplitude fluctuations, leading to lower average tensile forces. These discrepancies are attributed to an uneven inertia of the winding ring, caused by circumferential over-slip of the gear transmission (V–) belt (Fig. 10(B)). Therefore, an even weight distribution on the winding ring, which is generally controllable, has to be regarded for following validation tests.

![Figure 11](image1.png)

Figure 11  (A) Accordance of analytical and experimental winding angles for geodesic paths, with a coefficient of correlation $R^2 = 0.999$. (B) Tensile force measurements as a function of the take-up velocity by comparison of analytical and experimental CCD-plans to the prior $F_t$-scope. Dashed lines correspond to analytical tolerance fields of ±5%. Note that, the repetition of each test series is labeled as α(R).

![Figure 12](image2.png)

Figure 12  Comparison of analytical and experimental non-geodesic O-shaped paths with respect to each material substrate. Analytical tolerance fields of –10% and –30% are indicated by dashed lines. Note that, each performed test-series repetition is labeled as WP-O(R), respectively.
within an angle interval where normal force ratios are the lowest. In summary, as long as reliable velocity ratios and the setup tensile force amplitude are ensured, geodesic winding paths can have enhanced productivity.

Validation of non-geodesic winding paths

O-shaped winding paths

Experimental results for O-shaped non-geodesic winding paths confirm the occurrence of tow lateral slippage for both investigated substrate materials and modeled slippage coefficients $\lambda$. Hence, it was only partially possible to validate respective winding angles in accordance with analytics.

In Fig. 12, analytical and experimental measurements for $\lambda = 0.3$ and $\lambda = 0.5$ O-shaped paths are compared, showing that an increase of the stick behavior occurs independently of the interfacing material. This increased stick behavior is surprising since the opposite tendency (of the tape to laterally slip) was expected. However, a tape side inclination effect, occurred while winding paths with $\lambda = 0.5$, apparently explains this effect.

Validation of geodesic winding paths

Geodesic winding paths are fully validated. A comparison of geodesic path angle measurements with analytical results is illustrated in Fig. 11(A), confirming an excellent reproducibility through a coefficient of correlation of $R^2 = 0.999$. Even though remaining individual discrepancies over 10% are observed at $\alpha = 15^\circ$, winding angles did not deviate more than ±5% in average. Smaller deviations at $\alpha = 71^\circ$ are due to an over-slip of the gear transmission ($V-$) belt. A growing unstable behavior of geodesic paths below $\alpha = 30^\circ$ is dependent on the take-up velocity. According to Fig. 3(A), the range of the normal force ratio reaches a minimum at $\alpha < 30^\circ$, and trajectories are resilient to $F_t$-deviations (Fig. 11(B)), as long as $F_t$-magnitude does not drop to zero. Thus, a plausible explanation for the occurrence of such discrepancies is a tape's brief loss of tension within the guidance system. Higher standard deviations at lower velocities are attributed to friction-dependent tensile force amplitude peaks.

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tendency (Fig. 13). The faster increase in geodesic curvature at $\lambda = 0.5$ combined with the constant tape width generates a tensile force gradient across the tape's width. Consequently, the tow slightly twists prior to the nip-point, contacting the mandrel surface with only a fraction of its nominal width. The following increase of local normal pressure, due to the reduced nominal contact area, apparently leads to an increase of the coefficient of friction. An intensification of this effect is further observed for winding paths placed on a hoop-wound carbon-fiber layer (Fig. 12). It is generally assumed, that the local compaction of carbon fibers permits them to dig in and mechanically interlock more easily with adjacent substrate filaments.

Previous research describes a general tendency of a decreasing $\mu$ with increasing normal pressure.\textsuperscript{40-43} Additionally, a similar dig-in effect in filament level was also
Tow spreading does not occur in the present case, though, by application of thermoplastic coated tapes. These observations suggest that the increasing friction coefficients can indeed be associated with increasing normal pressure, resulting in an intensified filament-interlocking behavior. Fig. 14 illustrates this through micro section analysis, pointing out a higher stated, resulting in an increase of $\mu$ with increasing local normal pressure due to a realignment of parallel adjacent filaments. Results of Chow confirm that friction coefficients only decrease with increasing normal pressure because of tow flattening and spreading out, leading then to an increase of the real contact area and a decrease in the normal pressure. Tow spreading does not occur in the present case, though, by application of thermoplastic coated tapes. These observations suggest that the increasing friction coefficients can indeed be associated with increasing normal pressure, resulting in an intensified filament-interlocking behavior. Fig. 14 illustrates this through micro section analysis, pointing out a higher

Figure 17 Comparison of measured friction coefficients with the modeled slippage coefficients of O-/S-shaped winding paths. Stick-slip-tendencies are applicable for both material substrates

Figure 18 Comparison of the resulting coefficient of friction magnitude along O- and S-shaped winding paths. For $\mu_S$ measurements, the shifting motion of $\mu$ from the vertex to extremities is observed. Analytical tolerance fields of $\pm$20% and $\pm$40% are indicated by dashed lines. Note that each test-series repetition for O-shaped winding paths is labeled as $\lambda$-O(R); for S-shaped winding paths as $\lambda$-S(R)
interlocking behavior and preform density at normal pressures of 0.43 compared to 0.22 N/mm².

Fig. 16 presents the progress of the normal- and lateral-force measurements, stating a higher accordance of $F_n$ -measurements to analytics. Overestimation of $F_t$ at the path extremities indicates areas where the tape has laterally slipped. In Fig. 17 the modeled slippage coefficient and the maximum experimental friction coefficient are compared, demonstrating an overestimation of $\mu_s$ for O-shaped paths at the vertex point. The graph confirms the increasing stick behavior for both material substrate cases, specifying a higher resilience- and friction-coefficients for trajectories placed on a hoop-wound surface.

**S-shaped winding paths**

For S-shaped paths, the slippage behavior was higher and deviated more compared to O-shaped paths. Thus a full validation of winding paths was not achievable. Predominant analytical overestimation of the tape's measured lateral force progress confirms this behavior in Fig. 16.

A peculiarity of this case is that tape side inclination was not present. Results show a decrease of friction coefficient with increasing modeled slippage coefficient. Being triggered by the feed direction of each winding path, the higher slippage behavior is attributed to a dynamic drop of the nip-point normal pressure conditions, increasing the stick-slip-amplitude and leading to higher standard deviations. A comparison of analytical and experimental S-shaped paths supporting these assumptions is shown in Fig. 15, where trends for varied friction coefficients and substrate materials are summarized.

Further measurements confirm the trend of the stick behavior to improve on hoop-wound mandrel surfaces, setting up increasingly $\lambda$-values (Fig. 17). Contrary to O-shaped paths, S-shaped paths exhibit peaks of $\mu_s$ located respectively before and after the vertex point. The tape orthogonal realignment at the vertex and the increased local angle differences at the path extremities, near to geodesic/non-geodesic transition zones, lead to an increase in the geodesic curvature. The differences in the peak $\mu_s$ location are explained by the mandrels maintained feed direction after the vertex point, resulting in a shift opposite to the feed direction. Fig. 18 confirms this empirically when comparing the trend of friction coefficients along O- and S-shaped paths, indicating the shifted location of maximum $\mu_s$ values.

According to the results, non-geodesic winding paths can be designed when considering local $\lambda$ values. An adaption of force vectors at the nip-point in accordance with the respective winding method must be considered, so that limits of the coefficient of friction are constantly satisfied along the path. Note that the achieved coefficients of friction do not characterize the absolute limits for each material mating as expected. To do so, a proper validation of non-geodesic winding paths is needed, determining a feasible scope of the stick behavior in relation to the nip-point's normal pressure, relative velocity, and material topography.

**Conclusions**

This study investigated the validation of ring filament winding methods for unidirectional preform ply manufacturing. After establishing the tape guidance system configuration, geodesic and non-geodesic paths were implemented analytically and experimentally. For geodesic winding paths, the influence of the take-up velocity and the tensile force was considered, performing winding angles between 15° and 85°. Results show that the angles scope was highly reproducible, permitting process development from an economical point of view. Implementation of non-geodesic trajectories aimed to be analogous to symmetrical and asymmetrical unidirectional preform patterns. Accordingly, O- and S-shaped fiber trajectories were thus executed by parameterization of slippage coefficients and mandrel coverage materials. Only a partial validation succeeded, compared to analytics, due to the occurrence of lateral tape slippage. Comparison of measured tape lateral forces with analytics indicates areas where lateral slippage occurred. O-shaped paths presented higher stick-behavior than S-shaped paths. An additional tape side inclination effect, observed at $\lambda = 0.5$ for O-shaped paths, explains this trend of ascending friction coefficients with increasing slippage coefficients. An increase in the local normal pressure, intensifying the interlocking behavior between mating materials, is responsible for higher path stick persistency. Accentuated lateral slippage behavior for S-shaped paths is attributed to the absence of this effect. It can be concluded that non-geodesic winding paths can be modeled and validated considering local $\lambda$ values. An adaption of force vectors at the nip-point in accordance with the winding method is required, so that limits of the coefficient of friction are constantly fulfilled. The influence of normal pressure, process velocity, and surface topography on the absolute determination of the coefficient of friction has to be clarified in order to explain which mechanisms influence stick-slip behavior at unidirectional winding conditions.

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