Impact of winding parameters on the fiber bandwidth in the cylindrical area of a hydrogen pressure vessel for generating a digital twin

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Abstract
The wet winding process is an established manufacturing technology for the production of rotationally symmetrical components made of fiber-reinforced plastic (FRP), such as type-IV hydrogen pressure vessels. In this process, the FRP laminate is produced by continuously depositing an impregnated fiber band on the winding core in a winding pattern adapted to the component stress. Despite a long history of the process, there are shortcomings in the understanding of the process, without which further optimization in terms of cost and material efficiency will reach its limits in the future. Currently, the fiber band is assumed to have a constant rectangular cross-section in most simulations, which neglects manufacturing influences such as fiber spreading. The investigations carried out aim to extend the process understanding by a realistic description of the fiber bandwidth when deposited on the winding core. The investigations show that the fiber spreading, as well as the absolute fiber bandwidth, depend on the resin loading and the fiber band tension, independent of the winding pattern in the cylindrical area of a pressure vessel shaped winding core. In addition, the fiber bandwidth changes by 15%–20% during circumferential winding, depending on the machine movement.

KEYWORDS
composites, imaging, processing, sensors

1 | INTRODUCTION

The wet winding process has already been well-established on the market for decades as an economical manufacturing process for producing rotationally symmetrical components made of FRP, such as drive shafts and pressure vessels.[1] The FRP laminate is produced in a wet winding process by continuous deposition of a fiber band impregnated with low-viscosity resin on the winding core. The path of the fiber band on the winding core determines the fiber orientation in the laminate, while the resin loading and the fiber band tension influence the fiber volume content.[2] Both parameters (fiber orientation, fiber volume content) are adapted to the component stress in the design. However, there is a discrepancy between the part design and the actually manufactured
part, which results, among other things, from process-related manufacturing deviations that cannot be included in the design, such as overlaps, gaps, fiber displacements, and incorrect positioning of the fiber band. This leads to the necessity to over-dimension highly stressed and safety-relevant wound components, such as pressure vessels, in order to ensure that the mechanical properties of the laminate are maintained despite a discrepancy towards the design. Especially for CF-intensive 700 bar type-IV hydrogen pressure vessels with more than 70% contribution of the composite layer to the system costs, every reduction of CF-consumption is important.

One cause of this discrepancy towards the design is the assumption of a constant rectangular fiber band cross-section during part design and process simulation. This idealization neglects process influences such as fiber spreading on the fiber band geometry.

This article intends to expand the understanding of the behavior of the fiber bandwidth during fiber band deposition on a rotating winding core. The research presented in the paper focuses on the impact of process parameters during the application of helical and circumferential winding patterns in the cylindrical area of a vessel-shaped winding core. An infrared-optical camera system is therefore integrated into the production process on the principles outlined in a previous publication of the researcher. The principle of in-line determination of the fiber band geometry is a key element for the generation of a digital twin of the manufactured pressure vessels. As presented in Figure 1, the location-resolved information in the digital twin is created by a continuous target-actual-comparison between the position data of the winding machine and the in-line measured fiber band geometry and its position. By iteratively adapting the laminate design with the help of real quality data provided by the digital twin, process-induced defects in the wet winding process can be minimized and the currently necessary oversizing of the pressure vessels can be reduced, resulting in significant cost-saving potential.

2 | STATE OF THE ART

In the following, the wet filament winding process is presented. Thus, the most important factors and assumptions, currently known about the behavior of the fiber band during deposition, are summarized and the impact of manufacturing deviations on the laminate are outlined.

2.1 | Wet filament winding manufacturing process

A general wet filament winding process can be abstracted into three steps: Provision of fibers with a defined tension, fiber impregnation with a defined amount of low viscous resin, and the deposition of the impregnated fiber band around the winding core. Afterwards, the wound part is usually cured at elevated temperatures. The process begins at the creel rack where individual rovings are pulled-off at a defined tension (represented by the roving preload force $F_{\text{Rov}}$). At the impregnation unit, a liquid matrix material with a viscosity lower than 2 Pa·s is transferred to the fibers by immersion, roller, pressure, or vacuum impregnation. For the roller impregnation technique, the rovings are guided over a rotating roller, which is loaded with a defined resin film. The thickness of this resin film is defined by the gap between the doctor blade and the impregnation roller (see Figure 2).

After the impregnation unit, the rovings are combined to form a fiber band. The impregnated fiber band is then placed on the winding core by a deposit roll or a thread eye along the winding path. The winding pattern for a pressure vessel is usually a sequence of helical and circumferential layers. Circumferential layers cover in a band-to-band deposition the cylindrical part of the pressure vessel and serve to absorb radial forces. Therefore, the winding angle is close to $90^\circ$. A high compressive effect of this layer on the layers below controlled by the applied fiber band tension is as characteristic as the possibility of high winding speeds. Helical layers, however, allow for more
variations in the winding pattern due to different winding angles. These layers dominate the axial or the torsional strength of the part. During loading of the pressure vessel, the strain in circumferential direction is typically greater than the strain in longitudinal direction.\(^8\) By combining plies with different winding angles, the ply structure is determined according to the load assumptions for the part, resulting in a laminate that meets the mechanical requirements of the part. Calculation programs exist to determine the winding angles of each ply while taking into account the width of the fiber band.\(^7\) The underlying modeling of the laminate is based on the assumption of a rectangular cross-section of the fiber band (FB) with the fiber bandwidth \(b_{FB}\), the fiber band thickness \(t_{FB}\), and a fiber orientation \(\alpha\). The fiber orientation in the laminate structure of the component is equivalent to the winding path on the winding core. In modeling, a winding path is usually described by a one-dimensional line. This idealized deposition path results in the extension of the fiber band on the winding core after linking with the idealized cross-sectional area \((b_{FB}t_{FB})\).\(^2\) Thus, the winding path is stretched to the left and right by half of the fiber bandwidth \((b_{FB}/2)\). The quality of the wound component is essentially based on accurate deposition of the fiber band on the predefined path.\(^9\)

2.1.1 | Factors influencing the laminate quality of wound parts

To achieve the requested material properties of a winding part the fiber orientation and the fiber volume content need to be in accordance with the design as the mechanical properties are very sensitive towards these values. The determining values of the laminate properties (fiber orientation, fiber volume content) cannot be directly adjusted in the process.\(^10\) They result from the process parameters, which are the main control variables of the resulting laminate quality in wet winding processes, and geometrical factors.\(^2,11–14\)

- Resin temperature and resin load: the temperature of the resin determines its viscosity and thus affects both the resin loading of the roving and the ability to displace resin during compaction. Resin displacement and associated high fiber volume contents are increased by low resin viscosity.\(^15\) The resin load of the fiber band directly influences the layer thickness and thus the fiber volume content of the component. To simplify, it can be assumed that a lower fiber volume content in the laminate is proportionally accompanied by a reduction in component strength.\(^12\)
- Fiber band tension: The fiber band tension during winding directly influences the laminate quality, as it...
affects both the slip-free nature of the fiber band deposition and the compaction and pre-damage of the fiber material. High fiber band tension leads to increased compaction and thus increased fiber volume content.\cite{15,16}

- **Deposition angle:** The deposition angle determines the fiber orientation and the winding pattern, which influences the mechanical properties of the component. In the cylindrical area of a winding core normal force increases with increasing winding angle which results in a higher compaction strength. Lisbôa et al. found that the winding pattern of composite cylinders can have a strong influence on both maximum bearing load and absorbed energy under radial compression, whereas stiffness is less affected.\cite{17}

- **Surface curvature of the winding core:** The surface curvature of the winding core influences, on the one hand, the possible laydown angles and thus the design of the laminate and, on the other hand, the normal force, which is responsible, among other things, for the compaction of the laminate and thus the resulting fiber volume content and the laminate quality. Gerhardt et al. did numerical-experimental instability analyses on filament-wound rings and found a significant influence of imperfections (eigen buckling) on the mechanical stability during pressure tests.\cite{18}

### 2.2 Fiber spreading

Spreading is understood as the increase of the fiber bandwidth with simultaneous reduction of the fiber band height.\cite{19} The degree of spread \( s \) can be specified as a measure of the spread between two measuring points (MP), see (Equation (1)).\cite{20} Due to the normal force stress \( \left(F_{\text{N}}\right) \), which results from the applied fiber band tension \( \left(F_{\text{T}}\right) \) on a given surface, the upper filaments in the fiber band are pressed between the lower ones, pushing them to the side.\cite{21} For this purpose, the tangential force components between the filaments must overcome the internal (between fiber filaments) as well as external (to the substrate) frictional forces \( \left(F_{\text{R}}\right) \).\cite{22}

\[
 s = \frac{b_{\text{FB,MP}2}}{b_{\text{FB,MP}1}} \tag{1}
\]

Fiber spreading can affect the fiber bandwidth in two different areas during the winding process. On the one hand, the incoming fiber band is spread by guiding it over guide elements, the impregnation roller and spreader bars between the creel rack and the deposition roller. The spreading process homogenizes the fiber band geometry and ultimately the laminate quality.\cite{21} The extent of spreading is determined by the spreading devices used, their diameters, their arrangement and, for example, the delivery form of the rovings, the tex number of the roving, the resin loading and the process parameters of, for example, fiber band tension and winding speed.\cite{19} The final width with which the fiber band arrives at the deposition roll varies due to production-related tolerances in the starting material and fluctuations in the influencing variables mentioned.\cite{21} On the other hand, spreading can occur when or after the fiber band is deposited on the winding core. The extent of the spreading is influenced by numerous factors, such as the initial spreading, the surface curvature at the laydown location, the friction coefficient of the substrate and the fiber band tension.

Experimentally determined trends show: The lower the applied fiber band tension the more the fiber band spreads.\cite{6,20,22} The higher the (added) contact area between the fiber band and static spreading elements, the higher the spreading.\cite{6} In addition, twisting of the fibers negatively affects the spreading result as well as the reproducibility.\cite{22}

In a pressure vessel, the fiber spreading in the dome area is higher than in the cylindrical region.\cite{6}

The influence of the substrate on the spreading factor is related to the coefficient of friction. Experimental studies of the coefficient of friction in the winding process show that surface condition, winding type (wet or dry winding), resin viscosity (in wet winding) and fiber bandwidth have a significant influence on the coefficient of friction.\cite{23-25} In contrast, influences due to fiber band tension, winding speed and fiber material are found to be negligible.\cite{9,23-25} For the winding process, the fiber orientation of the surface layer on which a fiber band is placed shows a particular importance in relation to the winding angle. With parallel fiber orientation, the contact area as well as the possibility for interlocking is large compared to orthogonal (or angled) deposition, which results in a significantly larger coefficient of friction.\cite{24}

### 2.3 Reported impact of gaps and overlaps in laminates

The discrepancy between assumed and real fiber bandwidth as well as an inaccuracy in the positioning of the fiber band can lead to the formation of gaps or overlaps. Their impact on the laminate performance is examined in more detail below.

In the winding process, gaps occur when two fiber bands are placed next to each other with a larger gap or when the fiber bands are narrower than planned. Overlaps are caused by closer positioning of two fiber bands to each other or wider fiber bands than assumed.
Studies have shown that local defects in the form of gaps and overlaps in the laminate (in general, not specifically wound) have a negative effect on the mechanical properties of the component. Sawicki et al., for example, experimentally found a reduction in compressive strength between 5%–27% for flat test specimens with gaps or overlaps integrated in the laminate structure.\textsuperscript{[26]} Regarding the defect size, no increasing influence on the compressive strength was shown from a value of 0.762 mm.\textsuperscript{[26,27]} In studies on flat test specimens using the “defect-layer” method, Fayazbakhsh et al. show that gaps always have a negative effect on mechanical performance, while overlaps even increased stiffnesses.\textsuperscript{[28]} Heinecke et al. assumed gaps or overlaps in variations around 10% of the fiber bandwidth and calculated them as pure resin areas (gaps) or local areas of increased nominal stiffness (overlaps). Here, a reduction in strength of up to 22% was shown for overlaps.\textsuperscript{[29]} Gaps also led to a reduction in mechanical performance. In test panels with gaps and overlaps in the range of half a fiber bandwidth, Lan et al. found sink marks and defect propagation in overlying fiber layers up to local thickening at the component surface.\textsuperscript{[30]} Test specimens with these gaps showed a 5%–10% drop in in-plane shear modulus, while the overlaps led to an increase in modulus of up to 2%.\textsuperscript{[30]} Small gaps of 0.5 mm in extent showed no effect in either the microscopic analyses or the mechanical tests compared to defect-free reference plates.\textsuperscript{[30]} Croft et al. found on unidirectionally-reinforced test plates with integrated gaps or overlaps with an extension of one fiber bandwidth and twice the fiber band height that fiber movement closed all gaps with fibers.\textsuperscript{[31]} However, this leads to high fiber waviness in the laminate. For smaller voids (half fiber bandwidth), this effect is inhibited and the micrographs show pure resin areas.\textsuperscript{[31]} In filament winding, gaps and overlaps are expected to influence the pretension of certain areas of the fiber band that will be deposited above due to the different diameters of the substrate. Filaments that are deposited on gaps could compress and thus undulate while the pretension of filaments on top of overlaps could increase and thus lead to premature failure. Rach and Ivanovskii investigated the influence of the degree of overlap on the laminate tensile strength in fiber direction on unidirectionally wound aramid epoxy resin samples with a core diameter of 200 mm. An overlap of approx. 25% of the fiber bandwidth led to a reduction of the original strength by approx. 20%.\textsuperscript{[32]}

As stated it is agreed on the fact the manufacturing imperfections as gap and overlaps will affect the mechanical properties of a part and therefore are important to be investigated. This imperfections can be caused by unintended deviations of the fiber bandwidth in wet filament winding. To better understand the likelihood of their appearance during processing, the impact of processing parameters on the fiber bandwidth is evaluated with in this paper.

3 | EXPERIMENTATION

3.1 | Equipment

The process technology and materials used in the study are presented in the following. The results were obtained on a robot-based winding setup technology from the company Hille Engineering GmbH & Co. KG, Roetgen, Germany. The system consists of a linear axis on which the winding core rotates and moves translationally in front of a 6-axis industrial robot. The KR300 industrial robot from Kuka AG, Augsburg, carries the fiber laying head, which has four bobbin positions. The rovings are drawn off the fiber bobbins with a defined fiber band tension and guided to the impregnation unit, in which the rovings are impregnated as they pass over the impregnation roller ($d = 200$ mm, $\phi = 100$–$110^\circ$). The fiber band is deposited on the winding core by a deposition roller grooved to 24 mm, which is mounted on the band turning axis integrated in the laying head. The components of the laying head and the fiber course inside of it are shown in Figure 3. Due to the fact that the robot-based winding machine being used mimics the movements of a conventional machine, the results generated in this paper can be transferred onto other winding equipment. In circumferential positions, the fiber band path between this deposition roller and the deposition point on the winding core is approx. 8 cm. In addition to the rotation of the
band turning axis, this system concept allows the laying head to be swiveled during fiber band deposition at the dome areas, so that the deposition is also as orthogonal as possible to the winding core in this area. As standard, the tests were carried out with a swivel angle of 30°. The generation of the winding path including the suitable machine movement is done by means of the winding simulation software ComposicaD, Plastic Omnium S.A., Levallois-Perret, France.

For the inline detection of the fiber band geometry two A655sc infrared cameras from FLIR Systems Inc., Wilsonville, Oregon, USA, with an image resolution of 640 × 480 pixels, the standard 25° lens, and a maximum frame rate of 50 fps are used. The contrast in the recorded images is created by the higher temperature of the incoming fiber band in comparison to the cooler winding core, see section 3.3.

### 3.2 | Material

The winding core is represented by a thermoplastic liner from an unknown polyamide 6 type with metallic connecting elements (bosses). The dimensions of the liner used and its geometry are shown in Figure 4. Since the exact geometry of the bosses is sensitive information, it is not explained in detail.

Four carbon fiber rovings (ITS 50) from Teijin Carbon Europe GmbH, Wuppertal, Germany, with a fiber band count of 1600 tex are combined to form the fiber band. The low-viscosity resin system used is EPIKOTE Resin 04976 from Hexion Inc. of Columbus, Ohio, USA. Both, fibers and resin system represent a typical material combination for the production of type-IV pressure vessels. In order to increase the temperature of the resin and thus the contrast in the recorded image of the infrared camera, the trials are done without the hardener component. At a temperature of approx. 65°C, the viscosity of the pure resin is with about 240 mPas approximately the same as that of the resin system, which is processed at a temperature of 40°C. By adapting the viscosity of the used pure resin to that of the resin system, it is ensured that the fiber band behavior during deposition is representative for the real vessel manufacturing.

![Figure 4](image-url) Design of used winding core

### 3.3 | Methodology of fiber band detection

In the following, both helix and circumferential layers on different winding patterns are considered.

The positions of the two cameras are varied for circumferential and helical layers over the cylindrical area of the winding core and the dome areas. The infrared camera measures the temperature difference of the incoming, warmer fiber band compared to the substrate. However, the determination of the fiber bandwidth is only possible with this method if both outer edges of the fiber band can be reliably identified in the infrared images. Particularly in the case of band-to-band deposition of the warm fiber band in the circumferential layers, this results in limitations with regard to high winding speeds. With the aim of reliably detecting the influence of process changes on the fiber bandwidth, the edge detection of the fiber band deposition in the circumferential winding pattern has to be secured at any time during the winding process. Therefore, the fiber band is deposited in the circumferential layers with a gap between two adjacent fiber bands. This is achieved by artificially increasing the width of the fiber band from 22 mm for a band-to-band deposition with a slight overlap for a homogenous layer thickness to 33 mm in the winding program. This adjustment improved the quality of the detected data considerably, while only changing the winding angle slightly. The chosen winding angle is still considered representative for real part manufacturing. In band-to-band-deposition, neighboring fiber band edges could block each other so that spreading in this direction would decrease. Therefore, the reported results in this publication show the upper limit of the fiber band spreading.

For helical winding patterns two flat winding angles \( \alpha \) are chosen. While \( \alpha = 22.1° \) represents the smallest winding angle possible, passing just around the metallic boss, the winding angle of \( \alpha = 37.5° \) has its turning point just somewhere in the cured part of the dome area. The used winding patterns and their characteristics are summarized in Table 1.

For the determination of the fiber bandwidth from the collected data, an automatic algorithm is used. With this algorithm the characteristic value of the fiber bandwidth \( b_{FB}^* \) in a predefined temperature profile from the infrared images can be determined automatically. The fiber bandwidths is calculated from the rear and front fiber band edge. However for circumferential layers the temperature profile was evaluated as a horizontal line in the image. Therefore, for the calculation of the real fiber bandwidth \( b_{FB} \) from the fiber bandwidth \( b_{FB}^* \) determined by the algorithm is carried out taking into account...
the angle of deposition of the circumferential layer according to (Equation (2)). However, this is not necessary for helical layers in which the temperature profile was chosen vertically to the direction or the fiber band orientation in the infrared images.

\[ b_{FB} = b^*_{FB} \cdot \sin(\alpha) \]  

(2)

The values considered in section 4 are averaged over all frames of the video under consideration and the mean values are given as representative values for the data set. The standard deviation (sd) is taken into account as the error value, if not stated otherwise.

### 3.4 Process parameters and nomenclature for the presentation of results

In the following, the process parameters roving preload force \( F \), winding speed \( v \) and gap width of the doctor’s blade \( g \) are varied. For shorter naming in the legends of the diagrams, the fiber band tension force \( F_{FB} \), which is present in the fiber band right before deposition, is given in the unit Newton [N], whereby the roving preload force \( F \) is given as tension force per bobbin in the unit Newton [N], see Figure 3. This roving preload force leads to a tension of the fiber band. A roving preload force \( F \) of 16 N results in approx. 96 N fiber band tension force \( F_{FB} \) at the end of the laying head when four rovings are used. In the same setup, a roving preload force \( F \) of 4 N only results in approx. 28 N fiber band tension force \( F_{FB} \). The winding speed \( v \) of the circumferential layers is given as 0.6 m/s or 1.2 m/s. However, it needs to be considered, that these values are way lower, close the zero at the turning point, where the placement of the fiber band on the winding core changes direction. For helical windings, the take-off speed is approx. 0.4 m/s in the cylindrical area. At the turning point in the dome area this value is reduced strongly till 0 m/s. The specification of the opening gap of the doctor’s blade is in the unit micrometer \( [\mu m] \), whereby a small doctor blade gap results in a low resin loading. For the fiber band (before impact on the winding body), \( F = 16 \) N and \( g = 300 \mu m \) result in an fiber volume content of approx. \( FVC = 34\% \), at \( g = 200 \mu m \) of approx. \( FVC = 43\% \) and at \( g = 100 \mu m \) of approx. \( FVC = 52\% \) at the fiber band. The temperature of the resin bath in all tests is in the range of 65°C.

While the quantitative results on fiber band spreading presented in this publication are material specific with regard to the fiber and resin material being used, the evaluated effects of the roving preload force \( F \) and the doctor blade gap \( g \) on the fiber band spreading can be transferred on other materials. Since the robot-based winding machine being used in the investigation mimics the movements of conventional winding machines, the generated results are not considered equipment specific. The methodology for measuring the spread factor is generic and therefore applicable for every filament winding process.

### 4 RESULTS AND DISCUSSION

#### 4.1 Fiber spreading on the winding core

Since the fiber bandwidth can change in contact to the winding core due to fiber spreading, this effect is measured and discussed in the following. First, results of fiber spreading in circumferential layers is examined. Then the fiber spread in helical layers in the cylindrical area and at the dome will be presented. The dependence of the fiber spreading on different process parameters is determined and compared with the knowledge presented in the state of the art.

The degree of spread is calculated from the ratio of two fiber bandwidths \( b_{FB} \) at different measuring positions.

#### 4.1.1 Circumferential winding pattern

Spreading of the fiber band was found before and after the fiber band gets into contact with the winding core. The measured fiber spread in the free path between the deposition roller at the end of the laying head and the
deposition of the fiber band on the winding core (free path length approx. 8 cm) at $F = 16$ N is shown in Figure 5 (left). In the evaluations, a single infrared camera is mounted perpendicular to the fiber band and video sequences of 150–200 images (approx. 4 s) are analyzed. As the doctor blade gap $g$ increases from 50 μm to 400 μm for windings on circumferential layers, the degree of spread $s$ shows an increase from 1.04 to 1.15. This is more pronounced for windings on circumferential layers than on the liner. The deposition conditions on the winding core thus also influence the fiber spreading in the free path between the laying head and the winding core. At $F = 4$ N, there is no influence on the degree of spread in this area, irrespective of the substrate and resin loading (see Figure 5 [center]). At $F = 16$ N, on the other hand, an increase in the average degree of spread from 1.05 to 1.09 can be seen for windings on circumferential layers for $g = 200$ μm compared to $F = 4$ N. However, at $g = 50$ μm the average degree of spread was found to drop slightly with increasing roving preload force $F$.

In order to analyze the degree of spread for circumferential winding patterns on the winding core, the two infrared cameras are placed as shown in Figure 6. One camera, which is mounted on the laying head, records the fiber bandwidth at the deposition point (DP), represented by the first contact of the incoming fiber band on the winding core. Based on preliminary tests, it is assumed that most of the fiber spread is formed within the first 90° behind this deposition point. Therefore, the second infrared camera is mounted with a 90° offset on the linear axis.

Figure 6 (right) shows an example of the temperature profiles used to evaluate the fiber bandwidth. Since the slope in the temperature profile is similar regardless of the measurement location, the data sets are evaluated with similar parameters in the algorithm and used to calculate the mean degree of spread $s$ according to (Equation (3)). Its error ($\sigma_s$) is calculated according to DIN 1319-4 by the established principle of the Gaussian error propagation whereby the single value errors of

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**FIGURE 5** Fiber spreading between laying head (DR) and DP at 0.6 m/s winding speed

**FIGURE 6** Experimental setup for measuring fiber spreading in circumferential winding patterns and resulting temperature profiles
FIGURE 7  Spreading as a function of doctor blade gap for circumferential winding patterns on the pressure vessel

![Graph showing spreading as a function of doctor blade gap for circumferential winding patterns on the pressure vessel.](image)

$b_{FB,90°}$ and $b_{FB,DP}$ are approximated by their standard deviations $sd_{90°}$ and $sd_{DP}$.\[^{[34]}\]

$$s = \frac{b_{FB,90°}}{b_{FB,DP}} \cdot \text{mit} \sigma_s = \sqrt{\left(\frac{1}{b_{FB,DP}^2}\right)^2 sd_{90°}^2 + \left(\frac{b_{FB,DP}}{b_{FB,90°}}\right)^2 sd_{DP}^2}$$

(3)

Figure 7 shows the development of the degree of spread on the pressure vessel as a function of the winding pattern wound on top of (left) and the applied fiber band tension (middle) over the doctor’s blade gap. The degree of spread increases with an increased doctor’s blade gap in both cases. A higher resin load in the fiber band during deposition is caused by increasing doctor blade gaps $g$. Assuming that the resin acts as a lubricant between the fibers and thus reduces inter-fiber friction, the following hypothesis can be made on the basis of the measured data: The less the fibers are impregnated, the higher the forces required for fiber spreading. Low resin loadings thus lead to lower fiber spreading than high resin loadings.

The average degree of spreading $s$ for circumferential winding on a helical layer up to a doctor gap of $g = 200 \mu m$ tends to be slightly above that for fiber band deposition on circumferential layers. For the data point at $g = 200 \mu m$ on a circumferential layer, there is a large scatter of measured values which cannot be explained on the basis of the available data. The measured trend of higher degree of spread on helical plies is consistent with the literature, which predicts larger coefficients of friction and thus lower spreading due to the higher interlock when the incoming fiber orientation is parallel to the substrate.\[^{[24]}\]

The degree of spread at $F = 16 \text{ N}$ is on average higher than that for $F = 4 \text{ N}$, with standard deviations increasing with increasing doctor blade gap. While studies on guiding rollers in literature have tended to find an increase in fiber splay with a reduction in fiber band tension,\[^{[6,20,22]}\] an opposite trend is seen for fiber band tension with respect to winding on a winding core. With reference to the higher normal forces resulting from the applied higher fiber band tension, higher forces act on the fibers in the upper layers of the fiber band, thus indicating a widening. Thus, this result is in good agreement with the model conception of the acting forces during fiber band deposition.

The effect of fiber spreading is exemplified for the doctor blade gaps of $g = 50 \mu m$ and $g = 400 \mu m$ in Figure 7 (right). In the infrared images at the deposition point, at a low resin loading ($g = 50 \mu m$), hardly any influence can be seen due to the contact between the fiber band and the winding core. At $g = 400 \mu m$, the fiber band loaded with a high amount of resin shows a noticeable widening ($s = 1.28$). The discernible differences in absolute fiber bandwidth are addressed in section 4.2.

Overall, it can be stated, that there is fiber spreading between the laying head and the deposition point as well as on the winding core. Both degrees of spread must be taken into account with regard to the absolute fiber bandwidth. Multiplying the degrees of spread results in possible fiber bandwidths of more than 38 mm at the position 90° behind the deposition point for $g = 400 \mu m$.

4.1.2 | Helical winding pattern

To determine the fiber spread in the cylindrical area of the helical winding pattern, the cameras were placed to the measuring positions (a) and (b) shown in Figure 8. The degree of spread was determined according to Figure 8. Irrespective of the swivel angle $\beta$ of the laying head during fiber band deposition, a winding angle $\alpha$ of 22.1° ($s = 0.89$) shows a lower average spread than 37.5° ($s = 0.94$). A positive influence of the swivel angle on the fiber bandwidth, due to a laydown path adapted to the contour of the winding core, could not be determined.

In line with the trends determined for circumferential winding, an increase in the average degree of spread with higher values for the doctor blade gap in region (a) is evident at a winding angle of $\alpha = 22.1°$. The degree of spread
below 1 in the cylindrical area indicates that the fiber band becomes narrower as it is deposited from lower-right (a) to upper-left (b). The fiber band thus deforms slightly in a trapezoidal shape over the cylindrical area. The reason for the higher fiber bandwidth in the lower area (a) of the vessel results from the surface curvature of the dome area in combination with the pulling of the fiber band. During deposition on the cylindrical area, the fiber band initially runs in the open and only shortly before reaching the opposite dome area it does fall into contact with the winding core. During this movement, the fiber band is pulled with the fiber band tension force $F_{FB}$, causing it to contract over the length of the cylinder and reducing the fiber bandwidth while widening it at the curved dome area. Due to that contraction effect and the fact that the degree of spread in region (a) increases with higher doctor blade gaps, the fiber bandwidth decreases in helical layers with higher doctor blade gaps. This leads to decreasing values for the degree of spread since the bandwidth in region (a) is in the denominator in its formula (Figure 8 center).

### 4.2 Impact of winding parameters on the fiber bandwidth

In the following, results of the inline measured fiber bandwidth are presented, which originate from the measurements of the degree of spreading from section 4.1. Since the degree of spread only indicates a change in the fiber bandwidth, a consideration of the absolute fiber bandwidth is indicating the discrepancy towards the assumption of a constant fiber bandwidth in simulation. Depending on the process parameters, fiber bandwidths smaller than 24 mm are measured in the following. Since the 24 mm wide groove of the deposition roll only limits the maximum fiber bandwidth at the end of the laying head, smaller measured fiber bandwidths on the winding core allow the conclusion that the spreading of the fiber band in the laying head is not equally pronounced for all process parameter combinations.

In addition to the effects measured in section 4.1, namely that the fiber spreading is higher on helical layers as winding substrate compared to circumferential layers and also higher at $F = 16$ N fiber band tension instead of $F = 4$ N, Figure 9 also shows an absolutely higher fiber bandwidth under these conditions. Analogous to the degree of spreading, the measured fiber bandwidth $b_{FB}$ increases proportional to doctor blade gap $g$.

The increase of the fiber bandwidth with increasing resin loading due to the reduction of the frictional forces by the resin between the fibers within the fiber band as well as to the substrate is in line with expectations. Contrary to expectation, however, an absolutely higher fiber bandwidth of $\Delta b_{FB} = 8$ mm is shown on circumferential plies than on helical plies. Assuming higher frictional forces due to interlocking in an almost fiber-parallel

![Figure 8](image1.png)  
**Figure 8**  Spreading of helical winding patterns in the cylindrical area as a function of the swivel angle $\beta$, the winding angle $\alpha$ and the doctor blade gap $g$.

![Figure 9](image2.png)  
**Figure 9**  Fiber bandwidth as a function of doctor blade gap for circumferential winding patterns ($F = 16$ N, $v = 0.6$ m/s).
course between the incoming fiber band and the substrate, a smaller fiber bandwidth was expected on circumferential layers than on helical layers.\cite{24} One reason for the deviating measurement result may be a higher resin content on a winding substrate from circumferential layers than from helical layers, since more resin is pressed to the surface on circumferential layers than on helical layers due to the higher normal force component. However, the difference in fiber bandwidth is significant even at low resin loadings, leading to the suspicion of other influencing factors. The measured increase in fiber bandwidth with increasing fiber band tension is also in contrast to the literature.\cite{10} Analogous to section 4.1, this effect is assumed to be due to the stress distribution in the fiber band and the resulting higher displacement of fibers of lower layers by fibers of upper layers within the fiber band.

The effect of the fiber band tension on the fiber bandwidth is analogous to that of the circumferential windings in the cylindrical area of the helical winding (Figure 10, center, right). With increasing fiber band tension, the fiber bandwidth increases. For the (a) series of measurements, this increases from $b_{FB} = 25.5$ mm at $F = 4$ N to $b_{FB} = 32.4$ mm at $F = 16$ N. Regardless of the fiber band tension, an increase in the fiber bandwidth with higher settings for the doctor blade gap is shown. The variation of the swivel angle shows, analogous to the degree of spread, no influence independent of the winding angle (Figure 10, left).

The influence of the winding angle on the fiber bandwidth can be clearly seen in Figure 11. The fact that the fiber bandwidth tends to increase with increasing winding angle is essentially attributed to the higher normal force component. The closer the winding angle is to $\alpha = 90^\circ$, the greater the normal force acting on the fiber band. In the circumferential positions, which are wound with the steepest winding angle possible of $\alpha = 86.95^\circ$, the normal force acting on the fiber band is thus greatest. Consequently, this winding angle produces the widest fiber band ($b_{FB} = 35.5$ mm). With helical windings, a weaker normal force acts on the fiber band in the cylindrical part. The normal force is nevertheless higher at the steeper winding angle of $\alpha = 37.5^\circ$ than at the flat helical winding with $\alpha = 22.1^\circ$, which is expressed in the slight tendency towards a larger fiber bandwidth ($\Delta b_{FB} = 1$ mm in Area (b)).

### 4.3 Impact of deposition velocity on the fiber bandwidth

Mertiny and Ellyin found in windings on a tube that the fiber bandwidth shows a significant change between areas with motion changes (e.g., at the turning point) and areas of constant travel motion within one winding pattern of more than 10%.\cite{10}

Figure 12 shows the development of the fiber bandwidth in circumferential windings for two winding
speeds as an example. A dependence of the fiber bandwidth on the deposition speed is shown. At the turning points, where the winding speed of originally, for example, \( v = 1.2 \, \text{m/s} \) approaches zero, the fiber bandwidth is larger (\( b_{FB} = 28 \, \text{mm} \)) than in the center of the cylindrical area (\( b_{FB} = 23 \, \text{mm} \)), where the fiber band is delivered at almost constant speed. The change in fiber bandwidth with the change in movement is approx. 15\%–20\% for both winding speeds (\( v = 1.2 \, \text{m/s} \) and \( v = 0.6 \, \text{m/s} \)) and thus above the effects previously observed in the state of the art.

5 | CONCLUSION

The following findings were obtained from in-line detection of the fiber bandwidth using infrared cameras during deposition on a thermoplastic liner for pressure vessels. During circumferential winding, there is a strong dependence of the fiber spreading on the resin loading. Fiber spreading increases with higher fiber band tension force. Maximum spreading degrees of \( s \approx 1.3 \) are achieved for the highest resin loading (\( g = 400 \, \mu \text{m} \)) and the highest fiber band tension (\( F = 16 \, \text{N} \)).

The spreading on the winding body does not completely reproduce the total spreading of the fiber band for circumferential windings. A trapezoidal expansion is also measured between the exit from the laying head and the first contact point of the fiber band on the winding core (maximum degree of expansion \( s \approx 1.15 \) (\( g = 400 \, \mu \text{m}, F = 16 \, \text{N} \)).

In helical windings, the fiber band converges from the dome area over the cylindrical area of the winding core. The maximum measured degree of spread at \( g = 400 \, \mu \text{m} \) and \( F = 16 \, \text{N} \) fiber band tension is less than \( s \approx 0.8 \).

In the cylindrical region, the fiber bandwidth increases with the winding angle. The absolute fiber bandwidth is effected by the resin load and the fiber band tension in the circumferential part of the vessel independent of the winding pattern.

The fiber bandwidth is effected by the process flow during circumferential winding patterns.

It was shown that the fiber bandwidth shows a dependence on the investigated process parameters during fiber band deposition and thus deviates strongly from the assumption of a constant rectangular cross-section in the component design. This results in the potential for the component design to be able to map the effect of fiber spreading and the resulting overlaps also effecting the layer thickness in the design by a more realistic representation of the fiber bandwidth. In future, a digital twin of the inline measured data will be generated which provides a local resolution of certain manufacturing deviations during part production. This data would be of great benefit, for example, for stochastically simulation approaches including the representation of manufacturing deviations and the possibility to iteratively converge target and actual laminate design.[3]

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NOMENCLATURE

- \( \alpha \) fiber orientation/Winding angle
- \( \phi \) contact angle on impregnation roller
- \( \sigma_s \) standard error of degree of spread
- \( b_{FB} \) fiber bandwidth
- \( b_{FB}^* \) characteristic value of the fiber bandwidth in a predefined temperature profile
- CF carbon fiber
- \( d \) diameter
- DP deposition point
- \( F \) fiber band tension force
- \( F_N \) normal force
- \( F_R \) frictional force
- \( F_{Rov} \) roving preload force
- FB fiber band
- \( g \) gap width of doctor blade
- MP measurement point
- \( s \) degree of spread
- \( \text{sd} \) standard deviation
- \( t_{FB} \) fiber band thickness
- \( v \) winding speed

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