Path calculation, technology and opportunities in dry fiber winding: a review

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1. Introduction

Composites are rapidly evolving as an alternative to increase the performance and capabilities of existing materials. Thermoset composite products are generally made by impregnating dry fibers with resin or using a semi-finished product such as prepreg material which contains already partially cured resin. Although, high-quality composite products can be manufactured by using prepregs their processing generally incurs high raw material, storage and manufacturing costs. Due to the high costs in composite manufacturing, the industry is shifting towards manufacturing processes using dry fibers or bindered tape with an Out of Autoclave (OoA) curing. Dry preforms impregnated through liquid composite molding (LCM) processes are now replacing the use of prepreg material in manufacturing composite structural components.

Filament winding is one of the main composite manufacturing processes, in which composite parts are produced by laying fibers in prescribed patterns [1]. It is one of the most energy-efficient processes in composite manufacturing [2]. It is a well-established, fast and cost-effective process to manufacture fiber-reinforced composite parts [3]. Filament winding has been mostly used to manufacture axisymmetric composite parts. However, with the introduction of robotic manufacturing and advanced computing software, the winding technique has evolved into a highly flexible and efficient process, thus allowing more complex shapes and winding patterns. Three types of filament winding are generally employed in composite industry namely: dry fiber winding, wet winding, and prepreg winding. In some publications, the term ‘dry winding’ has been used to describe prepreg winding to differentiate it from wet winding [4–6]. For the winding of fibers without resin, the term ‘post-impregnation’ has been used [6]. In this study, it is referred to as ‘dry fiber/filament winding’.

The other two types namely wet and prepreg winding are well-established in the composite industry. However, both of these processes have some disadvantages. Table 1 shows the advantages and disadvantages of each type of winding process. Dry fiber winding has several advantages over the other types of filament winding [5,7]. It is characterized by low-cost manufacturing, high fiber content, accurate and repeatable fiber placement and controllable resin flow through LCM impregnation [7]. In this context, dry fiber winding also includes winding of roving containing binder material (mainly epoxy or thermoplastic). The binder is melted to act as an adhesive to fixate the layers of the preform. With the growing demand for using dry fibers, it is desirable to manufacture unidirectional preforms through winding at-
least in parts with rotation symmetry. Dry fiber winding will receive an increasing attention because stable preforms can be produced conveniently and economically with less wastage [8]. Therefore, it possesses a great potential to be a fully automated part of an out-of-autoclave (OoA) composite manufacturing process chain. However, compared to wet winding, dry fiber winding is still at an early stage in its development phase. Therefore, it needs to be investigated in detail and this review paper aims to provide an initial overview of this particular process.

When winding the fibers on a mandrel surface, the fiber trajectories and the resulting winding pattern have to be determined. Knowledge of differential geometry is used to obtain the winding trajectories [9]. Geodesics are defined as the shortest paths between two arbitrary points on a surface. They can simplify the calculation and the computational effort for obtaining winding trajectories on a surface. However, for design flexibility, the complete coverage of a mandrel surface, and especially for optimization purposes non-geodesic paths are used. Unlike geodesic paths, non-geodesic paths are not stable. Friction forces become essential to keep these paths from slipping and therefore the friction coefficient is a key parameter to be measured.

The objective of this study is to give an overview of the dry fiber winding process. It presents the state-of-the-art of mathematical approaches to generate winding trajectories, friction coefficient measurement techniques, winding equipment and software tools in filament winding. The concepts of differential geometry applied to filament winding are discussed first. Then the geodesic and non-geodesic paths and their mathematical formulations are discussed. In addition, non-analytical methods to generate winding trajectories are discussed. A brief overview of winding methods, simulation tools, and winding equipment is given in Section 4. In Section 5, the measurement of the coefficient of friction is introduced and the effects of various process parameters are presented. Section 6 highlights the topics and areas where scientific research is necessary to be carried out.

2. Application of differential geometry to filament winding

The theory of curves and surfaces is fundamental to develop the fiber path on a mandrel surface in filament winding. The mandrel is modeled as a surface in three-dimensional (3D) space and the fiber trajectories are represented by curves on this surface. The parametric representation is generally used to mathematically describe curves and surfaces because it is efficient for drawing and widely used in computer graphics [10]. Most of the shapes used in filament winding are surfaces of revolution. A detailed literature on this mathematical theory can be found in [10–15].

A fiber path modeled as a curve is described in terms of various parameters namely tangent (\( t \)), normal (\( n \)), binormal (\( b = t \times n \)) and curvature vectors (\( K, k_g, k_n \)) as shown in Figure 1. These variables describe the local properties of the fiber path. A comprehensive study on these variables and fundamental forms has been covered in [10–13]. A brief description of some of these variables and fundamental forms has been presented in Table 2 (with \( r \) being a curve supported on a surface \( S = S(u, v) \), \( u, v \) being the surface parameters and \( \hat{n} \) being the unit surface normal vector). These are necessary to understand the path generation process explained in the latter sections.

3. Winding path generation on surfaces of revolution

The most common mandrel shapes used in filament winding are surfaces of revolution. This section discusses the formulation and solution of geodesic and non-geodesic equations to determine the winding paths on mandrel surfaces.

3.1. Geodesic and non-geodesic winding

The winding paths followed by fibers on a surface must be stable, i.e. they should neither slip nor separate from the mandrel surface. A standard method to avoid slippage is to lay the fibers along geodesic paths [16]. A geodesic path can be defined as a locally length minimizing curve [16–18]. The geodesic path can simplify the calculation and the computational effort. However, it is a unique path for a particular starting point and winding angle and therefore restrictive. The calculation of a geodesic path on some mandrel surfaces is (locally) not possible and, therefore, the use of non-geodesic paths becomes
necessary. Non-geodesic paths may also be used to increase the design freedom and for the optimization of the mechanical properties [19–21]. They make use of the friction force to avoid slippage of fibers from the mandrel surface [22]. As a special case of non-geodesics, semi-geodesics are defined as paths with only a small deviation from the geodesic path [23,24]. Therefore, they require less friction force to keep the paths stable. Geodesic trajectories were mostly used in filament winding in earlier stages of composite manufacturing. However, with the progression of winding on complex geometries, non-geodesic paths are being widely implemented [25,26].

### 3.2. Geodesic trajectories

The differential equation of a geodesic path on a surface can be obtained by using two basic properties of a geodesic path:

#### 3.2.1. Geodesic curvature is zero

A curve on a surface is geodesic if its geodesic curvature $k_s$ is zero [27]. For a curve $r = r(s)$, supported on a surface $S = S(u(s), v(s))$, the geodesic equation can be expressed as [7,27]:

$$u''v'' - u'v' = -\Gamma^1_{11}(u)^3$$

$$-(2\Gamma^1_{12} - \Gamma^1_{11}(u)^2)v' + (2\Gamma^1_{12} - \Gamma^2_{22}(v)^2)u'(v')^2$$

$$+ \Gamma^1_{22}(v')^3$$

(1)

Equation (1) can also be expressed as a set of two dependent ordinary differential equations (ODE) [13,28]:

$$u'' + \Gamma^1_{11}(u')^2 + 2\Gamma^1_{12}(u'v') + \Gamma^2_{22}(v)^2 = 0$$

$$v'' + \Gamma^1_{11}(u')^2 + 2\Gamma^2_{12}(u'v') + \Gamma^2_{22}(v)^2 = 0$$

(2)

Or expressed as a set of four ordinary differential equations as:

$$u' = p$$

$$v' = q$$

$$p' = -\Gamma^1_{11}p^2 - 2\Gamma^1_{12} pq - \Gamma^1_{22} q^2$$

$$q' = -\Gamma^2_{11}p^2 - 2\Gamma^2_{12} pq - \Gamma^2_{22} q^2$$

(3)

where, $\Gamma^k_{ij}$, $i,j,k = 1,2$ are known as Christoffel symbols [10].
3.2.2. Minimal arc length

The arc length is minimal for a geodesic path. Therefore, the geodesic equation can be obtained by means of the calculus of variations [29]. The arc length in terms of the coefficients of the first fundamental form is given as:

\[ J = \int ds = \int \sqrt{E + 2Fv_u + Gv_u^2} \, du = \int f(u, v, v_u) \]  \hspace{1cm} (4)

According to the Euler-Lagrange differential equation [29], the minimum of this integral is given by:

\[ \frac{\partial f}{\partial v} - \frac{d}{du} \left( \frac{\partial f}{\partial v_u} \right) = 0 \]  \hspace{1cm} (5)

Using Equation (4) in Equation (5), we get the geodesic equation as:

\[ \frac{\partial f}{\partial v} + 2Fv_u \frac{\partial f}{\partial v_u} + \frac{\partial G}{\partial v_u} v_u^2 \\
- \frac{d}{du} \left( \frac{F + Gv_u}{\sqrt{E + 2Fv_u + Gv_u^2}} \right) = 0 \]  \hspace{1cm} (6)

3.2.3. Geodesics on shells of revolution

The general geodesic equations represented by Equations (2) and (6) become rather complicated to solve without numerical methods. For example, Kasap et al. [28] obtained the geodesic path on a surface by first using the finite-difference method and then solving the resulting non-linear algebraic equations by Newton’s method and a so-called iterative method. Details of the numerical treatment of geodesic differential equations can be found in [30].

**Liouville’s formula and Clairaut’s relation.**

Liouville’s formula and Clairaut’s relation are two well-known expressions which describe the geodesics of shells of revolution in terms of the coefficients of the first fundamental form and of the winding angle. Consider a surface of revolution defined by \( S(u, v) = \{ f(v)\cos u, f(v)\sin u, g(v) \} \), and let \( \alpha \) be the angle between a filament and a meridian line at a point on the surface also known as winding angle, then Liouville’s formula is given by [25,31]:

\[ k_\alpha = \frac{dz}{ds} - \frac{1}{2\sqrt{G}} \frac{\partial \ln E}{\partial v} \cos \alpha + \frac{1}{2\sqrt{E}} \frac{\partial \ln G}{\partial u} \sin \alpha \]  \hspace{1cm} (7)

As described already, the geodesic curvature \( k_\alpha \) for a geodesic is zero. The geodesic equation is then given by:

\[ \frac{dz}{ds} = \frac{1}{2\sqrt{G}} \frac{\partial \ln E}{\partial v} \cos \alpha - \frac{1}{2\sqrt{E}} \frac{\partial \ln G}{\partial u} \sin \alpha \]  \hspace{1cm} (8)

Clairaut’s relation [32,33] is a well-known formula which states that the geodesics on surfaces of revolution are characterized by

\[ \sin \alpha \sqrt{E} = \text{const.} \quad \text{or} \quad \rho \sin \alpha = r_1 \quad \text{(in polar coordinates)} \]  \hspace{1cm} (9)

where, \( r_1 \) is the polar opening radius of the shell of revolution and \( \rho \) is the radial distance from the axis of rotation. The relation is valid on each point of a geodesic path on any given surface and is fundamental to many filament winding processes. It says that if the radius increases, the winding angle has to decrease along a geodesic path on a surface and vice versa. A geodesic winding path is possible only for equal polar openings. The equation for obtaining the expression for the coordinates of the trajectory is given by [14,34]:

\[ u(v) = \int_{v_1}^{v_2} \frac{G}{E} \tan(\alpha) dv \]  \hspace{1cm} (10)

The equation for \( \alpha \) corresponding to a given surface of revolution is used in the above equation to obtain the final expression for coordinates of the trajectory. Figure 2 shows the geodesic path generation.

For e.g., in case a conical surface having \( r_1, r_2 \) and \( \beta \) as polar radius, equatorial radius and half-apex angle, respectively, the final geodesic path is given by Equation (11) [34]. Figure 3 shows a geodesic trajectory generated on a conical surface, a cylindrical and a spherical surface.

\[ u(v) = \frac{1}{\sin \beta} \left[ \sin^{-1} \left( \frac{r_1}{r_2} \right) - \sin^{-1} \left( \frac{r_1}{v} \right) \right] \]  \hspace{1cm} (11)

These figures show a geodesic path for a single stroke. Similarly, the strokes can be repeated to obtain a full coverage on the surface. However, it is not possible to obtain full coverage by using only geodesic trajectories. At least, local non-geodesic trajectories have to be used. Furthermore, the use of non-geodesic trajectories becomes essential as explained at the beginning of this section.

3.3. Non-geodesic trajectories

Non-geodesic paths are not stable on their own. The fiber will experience slippage when it deviates from a geodesic path and some kind of force is required to keep the fiber from slipping. The fibers can maintain a stable path by using the friction between the mandrel surface and the fiber. The condition for fiber stability is [35,36]:

\[ \mu > \left| \frac{k_g}{k_n} \right| \]  \hspace{1cm} (12)

where, \( k_g \) and \( k_n \) are the geodesic and the normal curvatures, respectively. \( \mu \) is the coefficient of friction which will be discussed in detail in Section 5.
The geodesic curvature is given by [34,35]:

\[ k_g = \frac{\cos \alpha}{C_0^2} \]

The normal curvature can be obtained from Euler’s theorem [12], which is given as:

\[ k_n = k_1 \cos^2 \alpha + k_2 \sin^2 \alpha \]  

(14)

where, \( k_1 \) and \( k_2 \) are the principal curvatures.

Using \( k_g \) and \( k_n \) in Equation (12), the non-geodesic equation can be obtained as [14]:

\[ \frac{dz}{d\varphi} = \frac{1}{2} E \tan \alpha \pm \frac{\mu}{\cos \alpha} \left[ \sqrt{1 + g_\rho^2} \left( k_1 \sin^2 \alpha + k_2 \cos^2 \alpha \right) \right] \]  

(16)

Specifically, \( f(\varphi) = h(z) \) and \( g(\rho) = z \) leads to:

\[ S(\phi, z) = \{ h(z) \cos \phi, h(z) \sin \phi, z \} \]  

(17)

Then the non-geodesic equation becomes:

\[ \frac{dz}{d\varphi} = \frac{\mu}{h^2} \left[ \frac{\sin \alpha \cdot \tan \alpha}{1 + h_z^2 \cos \alpha} - \frac{h_z \cdot \tan \alpha}{h} \right] \]  

(18)

where, \( (h(z), \phi, z) \) represent the polar coordinates for a meridian profile. For \( \mu = 0 \), this equation reduces to the well-known Clairaut’s relation [Equation (9)]. For given initial conditions, the non-geodesic trajectories can be calculated numerically using the Runge-Kutta method. For simple shapes such as a conical surface, an analytical solution can be obtained [32]. For example, Zhou et al. [36] proposed a so-called multi-micro-cone approximation method and plotted winding angles for non-geodesic paths with respect to different friction coefficients. They also found out that a larger friction coefficient is required for a smaller winding angle.

### 3.4. Non-geodesics for shells of revolution

**Polar coordinates.** The general non-geodesic equation for a surface of revolution \( (\phi, \rho) = \{ f(\rho) \cos \phi, f(\rho) \sin \phi, g(\rho) \} \) in a polar coordinate system is given by [37,38]:

\[ \frac{dz}{d\rho} = -\frac{1}{\rho} \tan \alpha \]  

\[ \frac{dz}{d\rho} = \mu \left[ \frac{\sin \alpha \cdot \tan \alpha}{1 + h_z^2 \cos \alpha} - \frac{h_z \cdot \tan \alpha}{h} \right] \]  

where, \( (h(z), \phi, z) \) represent the polar coordinates for a meridian profile. For \( \mu = 0 \), this equation reduces to the well-known Clairaut’s relation [Equation (9)]. For given initial conditions, the non-geodesic trajectories can be calculated numerically using the Runge-Kutta method. For simple shapes such as a conical surface, an analytical solution can be obtained [32]. For example, Zhou et al. [36] proposed a so-called multi-micro-cone approximation method and plotted winding angles for non-geodesic paths with respect to different friction coefficients. They also found out that a larger friction coefficient is required for a smaller winding angle.

**Spherical coordinates.** A surface of revolution in a spherical coordinate system is defined as: \( S(u, v) = \{ f(u) \sin v, f(u) \sin v, f(u) \cos u \} \). The general non-geodesic equation is given by [14]:

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**Figure 2.** Geodesic path generation.
This equation is suitable for a large number of shapes and simplifies the calculation significantly for shapes such as cylinders or ellipsoidal [14,34]. Equation (15) does not have an analytical solution. Therefore, a numerical solution is inevitable. This equation can be integrated using the fourth-order Runge-Kutta method [14,37]. Non-geodesic path generation is presented in Figure 4.

The non-geodesic paths on the surfaces of revolution are shown in Figure 5. The colors show the degree of deviation from the geodesic path. While the cylindrical pressure vessel needs non-geodesic paths only in the polar regions, the cone is depending on the surface friction almost everywhere. The here chosen winding pattern for the sphere relies on many degrees of geodesic behavior.

### 3.4. Alternative methods to generate winding paths on geometrical surfaces

Generally, four approaches have been discussed in the literature to obtain winding trajectories on surfaces. The first approach which has been already discussed solves the differential equations for geodesic and non-geodesic trajectories by numerical methods. Generating winding trajectories by solving the differential equations can sometimes be complicated and can require considerable mathematical effort. Furthermore, problems arise when using this method for irregular and polygonal surfaces. The other three alternative methods that have been proposed in the literature which can overcome these drawbacks are the discrete method, the geometric method, and patch winding. A good overview of these approaches can be found in [27].

**Figure 3.** Geodesic path on cone, cylinder and sphere.

**Figure 4.** Non-geodesic path generation.

\[
\frac{d}{du} \left( \sin \alpha \right) = - \left[ \frac{f_u}{f} \cot \beta \right] \sin \alpha \\
\pm \mu \left[ \frac{\left( f(u)f_u^2 + f_u^3 \cot \beta \right) \sin^2 \alpha}{f(u)\left( f^2 + f_u^2 \right)} + \frac{f^2(f_{uu} - f_u \cot \beta \sin^2 \alpha)}{f(u)\left( f^2 + f_u^2 \right)} \right. \\
+ \frac{2f_u^2 - f(u)f_{uu} + f^2}{f^2 + f_u^2} \right] \tag{19}
\]
3.4.1. Discrete method

In this method, the mandrel surface is decomposed into small elements. Then winding trajectories are approximated by a series of straight line segments on that meshed surface. This method can be used to generate trajectories for complex surfaces and is adaptable for both symmetric and non-symmetric surfaces. Liang et al. [39,40] used a so-called quasi-geodesic method and obtained non-geodesic winding trajectories on a surface of revolution by decomposing the surface into conical sections. Mazumdar and Hoa [41] obtained winding patterns on a non-axisymmetric triangular meshed surface by making use of geometric and trigonometric relations. Fu et al. [42] proposed a method which can be used for any convex surfaces, either axisymmetric or non-axisymmetric. In this method, the mandrel surface is expressed as a Stereo Lithography (STL) format and winding trajectories are obtained by creating propagation points on the STL model.

3.4.2. Geometric method

Discrete methods have been gaining attention with the introduction of advanced computing systems. However, in these methods, the geodesic path is calculated at first and then projected on a surface. In geometric methods which use only geometric information, it is possible to obtain geodesics directly on a surface [43]. Hotz and Hagen [44] presented a geometric method to obtain geodesics on any arbitrary surface. This method calculates geodesics by using the basic property that geodesics are straight lines on a plane. The advantage of this method is that it is independent of the complexity of a surface. Zhang et al. [27] presented a geometric method for computing geodesics directly on a regular surface. This method generates a geodesic curve by generating a sequence of geodesic points. It is suitable for parametric surfaces which are relatively flat and it can generate geodesics with modest accuracy.

3.4.3. Patch winding

Hongya et al. [45] proposed a method to generate winding trajectories on ‘abnormal’ mandrels such as airplane inlets and vanes. In this method, the mold surface is first meshed in order to obtain the coordinates of the mesh points. Then the slippage and bridging free points are selected to generate a winding path. The modeling of the mold surface was done through CAD/CAM software and the meshing was obtained through finite element software.

A comparison of these alternative methods and the differential geometry method to generate winding trajectories has been presented in Table 3.

4. Filament winding strategies, equipment, and programming tools

4.1. Winding strategies

The winding pattern plays an important role in determining the mechanical behavior of the component [46,47]. To obtain a required layup thickness suitable winding patterns must be selected. Generally, there are three types of winding patterns in filament winding namely helical, hoop and polar winding (Figure 6) [6,33,48,49]. The winding angle is the main characteristic which differentiates one type of winding from the other.

**Helical winding:** In helical or longitudinal winding, the filaments are wound in a helical path in

![Figure 5. Non-geodesic path on a cone, cylinder and a sphere.](image)}

Table 3. Comparison of differential geometry method and alternative methods.

|                      | Differential geometry method | Other methods          |
|----------------------|------------------------------|------------------------|
| Modeling of surfaces | Generates surfaces using differential geometry | Mesh based |
| Solution accuracy    | Accurate                     | Fairly accurate        |
| Extent over shapes   | Difficult to obtain for complex shapes | Easier to model complex shapes |
| Computational effort | High                         | Moderate               |
one direction at a particular winding angle $\alpha$, turn at the end of the mandrel and return in opposite direction at an angle $-\alpha$. The winding angle is between 5° to 80° and the winding pattern is repeated until the required thickness is obtained. This type of winding allows filament winding around corners, pins or polar openings. Helical winding can be used to wind a wide range of geometries but requires more advanced winding equipment.

**Hoop winding:** In hoop or circumferential winding, filaments are wound nearly perpendicular to the mandrel axis, i.e. the winding angle approaches 90°. It can be considered as a special case of helical winding. This type of winding is usually used along with other winding patterns to resist circumferential stress. It is generally applied only to cylindrical portions of a mandrel.

**Polar winding:** In polar winding, the fiber feed eye rotates around the longitudinal axis at determined fiber angles ranging from 0° to 5°. The fiber is approximately tangential to the polar openings of the mandrel. Polar winding is limited by the relationship between polar openings and the length of the part. It is mainly used to wind cylinders with length to diameter (L/D) ratio of less than 2.

Figure 6 shows the different types of winding patterns and Table 4 provides an overview of these different strategies.

### 4.2. Filament winding systems

With the introduction of computer control and winding generation software, the filament winding equipment has evolved from purely mechanical to computerized numerical control (CNC) machines and highly flexible robotic systems.

Different winding equipment technologies exist, varying in degrees of freedom of fiber guidance and mandrel motions. CNC winding machines have up to six axes of motion and, therefore, can be used to wind complex parts. In industry, they are mainly employed to wind symmetrical shapes such as pipes or pressure vessels in mass production. However, the need to manufacture complex parts with high precision, reduced cost and manufacturing time is resulting in the development of robotic-based winding technologies [51,52]. Moreover, they allow higher speeds, flexibility and can produce parts with better quality than a conventional filament winding machine [48]. A review of filament winding systems can be found in [53]. An analysis of existing winding equipment technologies and filament winding processes has been carried out by Minsch et al. [54]. The study investigated suitable winding equipment for numerous applications. Markov and Cheng [51] presented applications of robotic winding for composite materials and introduced a novel concept for robotizing the process of winding asymmetric parts.

Robotic winding is well suited to the dry filament winding on complex geometries. This method is characterized by full control over deposition, laying orientations, the amount of fiber material and homogeneity of fiber structure [9]. The robotic system offers precision and the constancy of winding tension to ensure the highest quality. Robotic deposition systems can be adapted for volume production. Several studies have been carried out on winding through robotic systems. Carrino et al. [55,56] developed a new deposition device which can wind more complex parts in short time and validated it experimentally. Polini and Sorrentino [57–59] studied the influence of geometric parameters on winding time in order to minimize it and ensure constant tension for achieving a high quality of the parts produced. Anamateros et al. [60] developed a robotic cell to manufacture structural parts having concave
Surfaces. Structural parts whose shape can be produced by sweeping a full section along a non-intersecting closed curve could be manufactured by this cell. Chan et al. [61] studied the accuracy versus speed relationship for low, medium and fast movement modes on a cylindrically shaped mandrel and found out that accurate winding can be obtained by the robot-based filament winding cell.

Some research groups have developed winding systems that can lay fibers from multiple roving-spools simultaneously. This enables high-speed winding and production time is reduced significantly. Paessler et al. [62], developed a ring winding technology which can simultaneously lay a large number of rovings circumferentially around a mandrel. The ring winding head consists of 12 radial movable arms and multiple payout eyes. Finkenwerder et al. [63] developed a ring-shaped arrangement of the fiber deposition unit. The winding ring is coupled to a robotic cell, which permits it to process continuous fiber on straight, curved or closed shape mandrels. The setup consists of a six-axis robot and can perform geodesic and non-geodesic winding. Besides standard winding methods, the winding ring permits the manufacturing of preform plies. Another development in robotic winding has been made by Cygnet Texkimp in collaboration with Northwest Composites Centre at the University of Manchester. They have developed a winding machine which is based on a nine-axis robotic winding concept. It is capable of building complex preforms for LCM processes.

Table 4. Overview of the filament winding strategies.

| Strategy | Type of winding and applications | Programming [50] |
|----------|---------------------------------|-----------------|
| HELICAL  | Geodesic winding, non-geodesic and a combination possible | Fiber divided into small segments and each segment is linearly approximated |
|          | Moderate speed                   | Program contains a number of blocks |
|          | Can be used to optimize the winding pattern on cylindrical shapes | Program bandwidth in helical winding is given by: |
|          | Applications: Pipes, pressure vessels, launch tubes, elbow shapes | |
|          |                                 | L = \frac{2\pi n}{k} |
|          |                                 | L = Programmed bandwidth |
|          |                                 | k = Number of divisions in each circumference |
|          |                                 | n = Number of circuits in each circumferential segments |
| HOOP     | Geodesic winding, non-geodesic and a combination possible | Can be performed with certain experimental inputs |
|          | High speed                       | Single block program is sufficient |
|          | Mainly for cylindrical sections  | |
|          | Used to create high consolidation pressure | |
|          | Applications: Pipes, cylindrical and toroidal pressure vessels, launch tubes | |
|          |                                 | Mandrel rotation is given by θ = \frac{h}{x} |
|          |                                 | θ = Mandrel rotation |
|          |                                 | ω = Translation of the carriage parallel to the mandrel axis |
|          |                                 | L = Programmed bandwidth |
| POLAR    | Non-geodesic winding             | Program contains a number of blocks |
|          | Low speed                        | |
|          | Applications: Domed ends, spherical components, road tankers | |

Types of robotic winding equipment forms [64]:

1. **Stationary Mandrel Winding**
   - **Robotic arm placement:** The robot end effector is fed by continuous roving. The head is rotated around the mandrel to lay the reinforcement, e.g. as depicted by Carrino.
   - **Centerless wheel winding:** In this type, the end effector is ring-shaped and it is rotated around the mandrel to lay the fiber on the mandrel, e.g. LOTUS filament winding process [65].

2. **Stationary Fiber Payout**

   In this type, the mandrel is stationary whereas the fiber payout is stationary. A robotic arm is used to move the mandrel, which causes the filaments to be laid on the mandrel. Examples are Markov’s concept of a robotic winding machine [51] or a tumble winding machine [14,20].

4.3. Programming tools and winding software

Computer aided design/manufacturing (CAD/CAM) have greatly improved the filament winding technology. Many software programs have been developed to simulate the filament winding process. Among the commercially available software are CADFIL, CADMAC [6], CADWIND [66,67], CAWAR [24,68], Abaqus (Wound Composite Modeler) [69] and ComposicaD [70]. Some have also been developed by research institutions such as PresVes developed by
As the last step, the winding program has to export the movement data in a suitable machine code. The options vary from simple text files to robot programming languages or the G-Code format used to operate CNC-machines.

5. Friction on mandrel surfaces

5.1. Mathematical description of the friction coefficient

For the calculation of non-geodesic paths, the determination of the friction between the fibers and the respective mandrel surface is essential. Figure 8 shows a roving on a surface \( S \). The force of the fiber tension \( f_t \) leads to a resulting force \( f_r \) acting towards the center of the curvature. It can be split into the normal force \( f_n \), which is balanced by the mandrel surface, and the lateral force \( f_b \), which has to be controlled by a friction force \( f_w \) in order to avoid slippage: \( ||f_b|| \leq ||f_w|| \) [22,72,73].

The slippage tendency \( \lambda \) (slippage coefficient in [72]) is defined as the ratio between the magnitude of the lateral force \( f_b \) and the normal force \( f_n \) [22,72]:

\[
\lambda = \frac{||f_b||}{||f_n||} = \frac{f_b}{f_n}
\] (20)

The friction coefficient (or coefficient of friction) \( \mu \) is then defined as the maximum allowable value of the slippage tendency [22]:

\[
|\lambda| \leq \mu = \frac{f_w}{f_n}
\] (21)

It can also be expressed by the relation between normal \( (k_n) \) and geodesic curvature \( (k_g) \) or the normal \( (R_n) \) and geodesic \( (R_g) \) radii of curvature.
5.2. Measurement of the friction coefficient

The common method to determine the coefficient of friction is to observe the starting point of the slippage while performing hoop winding. An overview of existing methods has been given by Koussios [74]. Several mandrel forms and influence factors have been tested in the last decades.

Early work on this topic has been done by Barking and Menges in the late 1970s [77,78]. They determined the coefficient of friction by circumferential winding on a sphere. Confirmed by various experiments of other authors [26,72,74,79,80], they also found out that the influence of the winding speed and of the fiber tension on the friction factor is negligible. Wells and McAnulty [26] then replaced the spherical with an elliptical mandrel to improve the accuracy of the measurements. They observed that there is merely a difference between the initial slippage point and so-called catastrophic slippage in dry filament winding. The friction coefficient for wet filament winding was harder to determine because the time span between initial slippage and completely losing adherence to the mandrel became significantly larger. The use of a PTFE spray as a mandrel surface treatment was also examined. It could increase the coefficient of friction by 0.15 in dry filament winding. Li and Lin [25] examined the influence of the coefficient of friction on the numerical solutions for non-geodesic paths of various geometries. Di Vita et al. [79] performed experiments based on the setup of Wells and McAnulty [26]. Glass-epoxy and carbon-epoxy prepreg rovings were used. The measured values of the coefficient of friction were about 0.2 larger for the glass fibers. Also, characteristic for broader rovings is that they are usually untwisted. A possible explanation is given by the interaction between the yarns and the velocity difference between inner and outer yarns. The friction coefficient values for wet fiber winding were about three times larger than those for dry fiber winding. The difference in results of [25,68,76] was pointed out and a standardization was proposed. It is assumed that the properties of the resin and the mandrel surface have a large influence. To investigate the influence of the mandrel surface an epoxy layer was used. This increased the coefficient of friction approximately by three times. A roughened epoxy layer decreases the friction of a twisted fiber bundle. It is presumed that the fibers, in this case, start rolling instead of slipping. Table 5 shows the values for the coefficient of friction for various types of fibers and mandrel surfaces.

The main focus of Madhavi et al. [80] was the (temporal) influence of the tackiness of already wound layers in the hoop winding of a pressure vessel. They found out that a time gap of approximately two hours will improve the tackiness and so simplify the winding of additional layers. Wang et al. [72] based their experiments on the setup of Koussios. Additionally, they examined the influence of the resin viscosity on the coefficient of friction: higher viscosity leads to an increase of friction.

6. Opportunities and challenges

Low-cost manufacturing, automation, repeatable high quality and excellent mechanical properties are the main objectives of future filament winding techniques. Dry filament winding can be a viable option. Nevertheless, the control of friction effects is the major challenge. Furthermore, new issues arise when process parameters are manipulated. To achieve the above-

\[
\frac{f_b}{f_n} = \frac{f_t/R_n}{f_t/R_g} = \frac{R_n}{R_g} = \frac{k_n}{k_t} \leq \mu 
\]

Table 5. Coefficients of friction [74].

| Fibers      | Mandrel                  | \(\mu\) |
|-------------|--------------------------|---------|
| Dry         | Polished aluminum surface| 0.15    |
| Twisted, dry| Roughened epoxy surface  | 0.20    |
| Wet         | Polished aluminum surface| 0.40    |
| Dry         | Smooth epoxy surface     | 0.50    |
| Untwisted, dry| Roughened epoxy surface | 0.60    |
mentioned objectives, the respective research areas are pointed out in the following section.

6.1. Winding trajectories

The focus of research has shifted to winding shapes that are either not possible or very difficult to wind with the traditional winding. As discussed in Section 3.4, with the introduction of advanced computing systems, new methods to generate winding trajectories on irregular, non-axisymmetric and polygonal shapes have been gaining attention. Although some work has been carried out by research teams by using non-analytical methods, generating slippage- and bridging-free geodesic and non-geodesic trajectories on complex shapes is still an issue. All these non-analytical methods have their own disadvantages. For example, the discrete methods cannot generate paths directly on a surface whereas the geometric methods are less suitable for the computation of ‘massive’ geodesics on a surface. Therefore, research effort is required to increase the extent and accuracy of these alternative approaches.

6.2. Fiber deposition systems

As discussed in Section 4.2, robotic filament winding can be used to wind complex geometries. The challenge will be to develop deposition systems that allow fast and accurate placement of dry fibers on the mandrel surface in a minimum amount of time. Deposition systems must be flexible enough to lay fibers on complex trajectories without causing fiber unfastening or speed variations. Therefore, highly flexible and efficient deposition systems like the aforementioned ring winding head have to be developed.

6.3. Friction and measurement of the friction coefficient

The friction arising during the lay-up of fibers onto the mandrel surface or on already wound fiber layers is crucial for the processing of dry fibers. The manipulation of the acting surfaces in order to increase the friction may become necessary. This can be achieved by roughening the mandrel surface and/or increasing the tack of the rovings, e.g. by application of binder material. Moreover, the usage of mechanical fastenings, e.g. holding pins or compacting mechanisms, can be considered. State-of-the-art for the determination of the friction coefficient is the image analysis of the slipping point of rovings on a mandrel. Although numerous efforts have been made to investigate influencing parameters, not all of them have been examined sufficiently. Also, possible correlations of these parameters have yet to be considered. Furthermore, since the visual detection is a rather simple method, the accuracy and repeatability are improvable. A standardized, precise and reliable measuring method should be developed.

6.4. Effects of process-related parameters

The filament winding process depends upon a number of interdependent parameters. Complex winding trajectories can cause fiber unfastening or speed variations due to abrupt changes in the curvature. Therefore, controlling the winding tension is still a challenging topic. In case of dry fiber winding, the roving tension and the fiber guidance system may also induce roving deformation [81].

A high winding speed is necessary to obtain an acceptable production rate. Yet, higher winding speed leads to a lower accuracy of the movement of the deposition eye. This, in turn, affects the ability of the winding system to exactly perform the described path. The winding accuracy also depends on the methodology of computing the path and coordination between the robot arm and the mandrel. Besides, the winding path itself is influenced by the winding angle, the starting point, the winding method and the friction coefficient.

6.5. Impregnation challenges

The preforms produced by dry filament winding have to be impregnated using LCM techniques such as vacuum-assisted resin infusion (VARI) or resin transfer molding (RTM). A very important parameter in LCM processes is the permeability of the reinforcement structure. If a binder or tackifier material is used to maintain the shape of the preform, the effect of a binder on preform permeability and the resin flow must be evaluated. The dry fiber winding process further needs a study both numerically and experimentally on the ability to be completely impregnated. Also, the handling of dry wound preforms from the winding mandrel to the impregnation unit has to be considered. Moreover, producing low-cost, reusable or multifunctional mandrels can drastically reduce the manufacturing cost of parts in filament winding, e.g. collapsible, core-less, water-soluble sand or segmented mandrels [6,47,82].

6.6. Industry applications and need for the future

As compared to the wet winding, in dry fiber winding better impregnation can be realized through vacuum infusion or RTM and voids can be minimized.
Therefore, higher strength parts can be manufactured at a reduced weight. A report on hydrogen pressure vessels [83] showed that weight can be reduced by using dry fiber winding and therefore cost savings can be achieved. Manufacturing cost decreases as the throughput increases. Therefore, it is necessary to increase winding speed and still achieve the same quality. According to the report [84], dry tape winding within a hybrid filament winding and automated fiber placement (AFP) process can be used for high-speed winding. This leads to a significant reduction in weight and savings in the manufacturing costs. Still, these advanced manufacturing processes are in their early stages. However, the main aim is to use dry fiber to achieve lower material usage, lower cost, and higher efficiency. Therefore, the demand for dry fiber and tape winding is expected to grow in the near future. Applications in the energy sector are mainly pressure vessels and pipes. In the aerospace segment, dry fiber winding can be used to manufacture high-performance components with a superior external finish such as nozzles, conical shapes, launch tubes, and struts.

7. Conclusion

An overview of the filament winding techniques has been presented in this study and particular attention has been given to dry filament winding. It is seen as a promising process to be a part of an OoA manufacturing process chain for producing high-quality composite parts at reduced manufacturing costs. The application of differential geometry to generate geodesic and non-geodesic trajectories on a mandrel surface has been presented. Besides, alternative methods to generate winding trajectories have been introduced. The techniques to measure the friction coefficient which becomes an important parameter during non-geodesic winding have been discussed. Common winding strategies, programming tools to simulate the winding process and filament winding equipment have been reviewed. Conclusively, open scientific topics were pointed out.

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