Development of Fast Local Analysis Tool for Optimized Laser Assisted Tape Winding

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**UNIVERSITY
OF TWENTE.**

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DISSERTATION

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On the front side, an illustration of the additive process of laser assisted tape winding with the brain of OTOM software developed in this thesis is shown. On the backside, Eulerian computational framework is demonstrated which was widely employed in this thesis.

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Abbreviations:

2D	Two-dimensional
3D	Three-dimensional
<i>Ra</i>	Average mean square
<i>RMS</i>	Root mean square
BRDF	Bidirectional reflectance distribution function
Big-M	Big mandrel
BC	Boundary condition
CF	Carbon-fiber
COV	Coefficient of variation
CNG	Compressed natural gas
FRTP	Continuous fiber reinforced thermoplastic
CFRTs	Continuous fiber-reinforced thermoplastic
CHTC	Convective heat transfer coefficient
EC	Emission coefficient
FRP	Fiber reinforced polymer
FRTPCs	Fiber reinforced thermoplastic composites
FVC	Fiber volume content
FBG	Fiber-Bragg grating
GA	Genetic algorithm
GF	Glass-fiber
G/HDPE	Glass-reinforced high-density polyethylene
HTC	Heat transfer coefficient
ICs	Initial conditions
LATP	Laser Assisted Tape Placement
LATW	Laser Assisted Tape Winding
MHC	Micro half cylinder
Narrow-T	Narrow tape
OTOM	Optical Thermal Optimization Model
PEEK	Poly Ether Ether Ketone
PA	PolyAmide
PE	PolyEthylene
PVDF	Polyvinylidene fluoride
PP	Polypropylene
PLC	Programmable Logic Controller
SOP	Single objective problem
SLR	Single-lens reflex
Small-M	Small mandrel
STD	Standard deviation
TIC	Thermal imaging camera
TP-ATP	Thermoplastic automated tape placement
UD	Unidirectional
VSCSEL	Vertical-cavity surface-emitting laser
Wide-T	Wide tape

Abstract

Continuous fiber reinforced thermoplastic (F RTP) lightweight composite products have become more and more popular for many engineering applications thanks to their unique properties like high specific strength, corrosion resistance, recyclability and tailorability. A more sustainable future and society can be fostered by using F RTP composites since they provide a relatively long service life with less maintenance need and a lower energy consumption during manufacturing. Laser-assisted tape winding and placement processes (LATW and LATP) are some of the promising manufacturing techniques to produce advanced thermoplastic composite components. A rotating mandrel or liner is used in LATW processing. A fully automated single step manufacturing can be achieved in LATW and LATP processes when the F RTP prepreg tapes are consolidated “in situ”, which can reduce the production costs and eliminate post consolidation or curing steps. Despite the advantages of these manufacturing techniques, it is a difficult task to predict and control the process temperature which is driven by the laser irradiation, the reflections, the local tooling geometry and the process parameters. It is vital to thoroughly analyze the process temperature, which is critical for the resulting part properties and performance. The focus in this thesis is on the winding of pipes and pressure vessels made of F RTP composites. The performed research was a part of the EU funded *ambliFibre* project with an ambition of developing a model-based in-line process control for LATW processes. A Proper bonding and consolidation of the deposited or wound tapes include the development of intimate contact and then healing of the polymeric matrix. Both phenomena are highly temperature-dependent, therefore optimum process settings have to be described prescribed to keep the local process temperature at a desired level which is a challenging task. The long term objective of this thesis is to achieve a robust LATW process by compensating the variability in the manufacturing process resulting in repetitive and predictable part properties and performance. The complex geometry, varying tooling curvature, anisotropic optical and thermal properties of the F RTP tapes used in LATW make it difficult to describe, predict and optimize the process temperature. The work presented in this thesis takes the first steps towards the long term objective by developing the key building blocks. The first step to the development of a generic physics-based process model of the LATW process comprised a number of experimental studies to generate quantitative data

that can be used as input for subsequent modeling activities. Firstly, the optical properties of several prepreg tapes were studied experimentally to acquire the required information for accurate modeling of the optical and thermal phenomena. The transmittance of the tapes was found to be negligible whereas the reflectance was found to be 9.8% - 11.8% for different prepreg tapes. The anisotropic reflectance measurements, as obtained through a gonioreflectometry, were employed to fit the bidirectional reflectance distribution function (BRDF) which was used to simulate the anisotropic or non-specular reflection of the FRTP tapes. Secondly, the knowledge of the LATW process was enhanced by quantifying the variation in the process temperature during continuous adjacent hoop-winding of a full composite, type-IV pressure vessel made of glass-reinforced high-density polyethylene (HDPE). Placing additional layers on a previously heated substrate, as part of the continuous nature of the manufacturing process, together with the variation in material and process parameters caused a certain variation in the process temperature which was quantified via the coefficient of variation (COV). Next, the temperature evolution was described and predicted during the LATW process of a type-IV HDPE pressure vessel. A new local optical-thermal model was coupled with a global thermal model for the simulation of continuous adjacent hoop-winding cases. The influence of the pressure vessel size on the process temperature was investigated using the validated process model. Afterwards, the effects of winding angle, pressure vessel size and tape width on the process temperature were investigated in a discontinuous LATW process by using the developed generic optical-thermal process model. It was observed that an increase in mandrel curvature resulted in higher process temperatures for the substrate and lower values for the tape. Furthermore, a larger tape width caused larger local temperature variations at the edges of the tape/substrate. Lastly, an LATW process of a cylindrical pressure vessel with a dome shaped head was optimized, involving complex tooling geometries on which the laser irradiation and temperature profiles changed as a function of time. A new process optimization framework was introduced by means of a genetic algorithm (GA). The objective was to keep the process temperature within the desired temperature limits during winding of FRTP tapes onto complex curved surfaces. It was shown that the maximum laser intensity increased approximately by 80% and the process temperature changed by 80°C at the intersection of the cylindrical and dome section of the pressure vessel in the non-optimized case. The optimization tool significantly improved the process temperature stability to approximately 1°C variation by changing the total laser power between 30% and 175% of the reference (non-optimized) laser power. The findings of this thesis are bundled in a broader perspective and the next steps to achieve a robust LATW process are assessed. Finally, the scientific conclusions are drawn and future recommendations are made to improve the predictability of the developed process models and optimization tools.

Samenvatting

Thermoplastische lichtgewicht composietproducten zijn steeds populairder geworden voor veel technische toepassingen dankzij hun unieke eigenschappen zoals hoge specifieke sterkte, corrosiebestendigheid, recyclebaarheid en aanpasbaarheid. Dit type producten kan helpen bij het bouwen van een duurzamere toekomst, waarbij tegelijkertijd het belang wordt benadrukt van hun storingsvrije kwaliteit en veilige werking. Geavanceerde technieken zoals laser-assisted tape winding/plaatsing (LATW / LATP) -processen zijn veelbelovend om ze te vervaardigen. De LATW is een geautomatiseerd proces om buisachtige vezelversterkte polymeercomposieten te produceren, vergelijkbaar met het LATP-proces. Het LATW-proces wordt uitgevoerd door een prepreg-tape rond een doorn of voering te wikkelen, terwijl in het LATP-proces een thermoplastische prepreg-tape iteratief wordt neergelegd voor het vervaardigen van een onderdeel. Ondanks de mogelijkheden van de processen is het nogal moeilijk om de parameters en verschijnselen van het fabricageproces te beheersen en te voorspellen. Het is daarom van het grootste belang om deze processen onder de knie te krijgen om de gewenste productkwaliteit en betrouwbaarheid te garanderen om de duurzaamheid te bereiken.

De focus in dit proefschrift ligt op de thermoplastische producten voor buizen en drukvaten die deel uitmaakten van het door de EU gefinancierde ambliFibre-project met de ambitie van inline procesbeheersing. Een goede hechtingsconsolidatie vereist optimale procesinstellingen om de consolidatiedruk, tijd en temperatuur op het spleetpunt op een gewenst niveau te houden, wat een uitdagende taak is in de LATW / LATP-processen. Van de parameters is de procestemperatuur de belangrijkste en meest uitdagende factor die zowel tijdens het proces kan worden voorspeld als gecontroleerd. De temperatuurvoorspelling vereist kennis van het proces en tapematerialen. Deze kennis is gedeeltelijk beschikbaar in de literatuur. Een generiek voorspellend model vereist echter uitgebreide informatie, b.v. over anisotrope reflectie of continue LATW die nog ontbreken.

In dit opzicht worden de optische eigenschappen van verschillende prepreg-tapes eerst bestudeerd om de vereiste informatie voor modellering te verkrijgen. De transmissie van de tapes werd verwaarloosbaar bevonden, terwijl de reflectie 9.8% - 11.8% was voor verschillende prepreg-tapes. De anisotrope reflectiemetingen, zoals verkregen door middel van

een gonioreflectometrie, werden gebruikt om te passen bij de bidirectionele reflectieverdelingsfunctie (BRDF). Ten tweede wordt de kennis van het LATW-proces ook vergroot door het analyseren van experimentele gegevens van continue aangrenzende hoepelwikkeling van drukvat type IV gemaakt van glasvezelversterkt hoge dichtheids poly ethyleen (HDPE). Het in een continu proces plaatsen van extra lagen op een eerder verwarmd substraat en variatie in materiaal en procesparameters veroorzaken een variatie in de procestemperatuur die wordt gekwantificeerd via variatie coefficient (COV). Deze twee onderzoeken leveren ontbrekende experimentele informatie in de literatuur om een generiek fysisch model voor het LATW-proces te bouwen.

Vervolgens wordt de temperatuurevolutie beschreven en voorspeld tijdens het LATW-proces van een type-IV HDPE-drukvat. Een nieuw lokaal optisch-thermisch model is gekoppeld aan een globaal thermisch model voor de simulatie van continue aangrenzende hoepelwikkelbehuizingen. De invloed van de grootte van het drukvat op de procestemperatuur wordt onderzocht met behulp van het gevalideerde procesmodel. Daarna worden de effecten van wikkelhoek, drukvatgrootte en tapebreedte op de procestemperatuur onderzocht in een discontinu LATW-proces door middel van de parameterstudie. Opgemerkt wordt dat een toename in de kromming van de doorn resulteert in hogere kneppunttemperaturen voor substraat en lagere voor tape. Bovendien veroorzaakt een grotere tapebreedte grotere lokale temperatuurvariaties aan de randen van de tape het substraat.

Last but not least wordt de complexiteit van krommingsverandering tijdens de LATW/LATP op complexe onderdeelgeometrieën aangepakt door simulatie en optimalisatie van de wikkeling / plaatsing op de koepel van het drukvat. Aangetoond wordt dat de maximale laserintensiteit ongeveer met 80% toeneemt en de procestemperatuur verandert met 80°C op het snijpunt van het cilindrische en koepelvormige gedeelte van het drukvat. De optimalisatietool verbetert echter enorm de procestemperatuur met ongeveer 1°C variatie door het totale laservermogen te veranderen tussen 30% en 175% van het referentie (niet-geoptimaliseerde) laservermogen.

De bevindingen van het proefschrift worden in een breder perspectief gebundeld in de discussiesectie die de lezer de mogelijkheid biedt om dieper inzicht te krijgen in de snelle in-line procesbeheersing.

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Chapter 1

Introduction

1.1 Background and motivation

Fiber reinforced polymer (FRP) composites emerged in the beginning of the 1940s as a potential replacement to metallic components [1–4]. The FRP composites are characterized by their high specific strength and stiffness values surpassing the values for most of the metals as shown in Figure 1.1. The unique properties of FRP composites are determined by the combination of relatively light and high strength/high stiffness fibers, such as carbon and glass fibers, that are embedded in a lightweight polymeric matrix. Optimal properties of the FRP composite structures can be achieved by placing the fibers in the primary loading direction, also known as elastic tailoring.

Fig. 1.1 Specific strength and density of numerous engineering material classes [1].

The manufacturing of FRPs has for a long time been rather time and effort consuming. Often manual labor is required to carefully lay out the fibers, in the form of unidirectional (UD) or woven plies. By stacking multiple plies on top of each other with the fibers aligned in designated directions, the mechanical properties of the product can be designed at wish. The plies are either pre-impregnated with a thermoset resin or an additional impregnation step is required to embed the fibers within the polymeric matrix. Subsequently, time-consuming autoclave processing is required at elevated temperature and high pressure to generate a fully continuous thermoset matrix, free from voids and fully chemically cured, to provide the composite part its final and unique properties. Although the high specific properties undoubtedly may lead to a significant weight saving for many applications, the high costs associated with the manufacturing of the FRPs limit the widespread use of these materials.

The development of FRP composites based on a thermoplastic matrix, initiated in the 1980s, may provide a breakthrough in the use of composite materials for a broader range of applications. The thermoplastic nature of the matrix provides, in principle, easy manufacturing approaches based on heating the material up to a temperature high enough for the matrix to become soft and ductile. Then, the material can be shaped into the desired form by processes such as bending and press forming, and cooled down to ambient temperatures to maintain the product form. In this way, increased production rates are possible potentially lowering the manufacturing costs. Also, welding of separately manufactured thermoplastic composite products has become an attractive option for assembly.

1.2 Laser-assisted tape winding

The thermoplastic nature also provides new opportunities to the manufacturing of more complex products with local variations in ply layup and/or characterized by hollow sections, such as pipes and pressure vessels as shown in Figure 1.2. Versatile manufacturing methods were employed during decades such as the filament winding of fiber reinforced thermoset polymers which was initiated in the early 1940s [3]. New manufacturing techniques have been developed over the last decade to deposit thermoplastic tapes at designated locations through placement and winding. Especially, the most recently developed laser-assisted approaches hold a great promise to the automated manufacturing of complex products. In this way cost-effective, high-quality products can be manufactured at a fast pace and with reproducible mechanical and/or functional properties.

This thesis is concerned with the Laser Assisted Tape Winding (LATW) process. A description of the process is shown in Figure 1.3. A laser is used to heat the tape and substrate to a high enough temperature to soften both materials. The tape is composed of strength-

Fig. 1.2 LATW products including pressure vessel and pipe.

Fig. 1.3 LATW process main elements in schematic and real views.

ening fibers, mostly oriented in the length direction of the tape and it is pre-impregnated with a thermoplastic matrix, such as Poly Ether Ether Ketone (PEEK), PolyAmide (PA), PolyEthylene (PE), Polyvinylidene fluoride (PVDF), and Polypropylene (PP). The rotation of the liner/mandrel moves the softened materials to the region under the roller where the tape is pressed on top of the substrate, the so-called nip point. In the small amount of time available, consolidation of the tape to the substrate has to take place providing strength to the tape-substrate interface.

1.3 The role of LATW process control

The quality of the manufactured product is strongly influenced by the temperature at the nip point where tape and substrate are consolidated. If the temperature is too low or the tape

Fig. 1.4 The role of the modeling in the ambliFibre project [5].

velocity is too high, insufficient time is available for proper development of the interface strength. If the temperature is too high, degradation of the polymer matrix may occur jeopardizing the quality of the final product as well. Even the placement accuracy of the heated, hence soft, tapes on the mandrel is of importance because a slight misalignment of the tape on the mandrel will potentially lead to uncovered areas on the substrate culminating in either porous regions or matrix-enriched regions in the final product. Evidently, process control constitutes a very important part of the success of the production process. Hence, appropriate control strategies are required to fully embrace the potential of LATW as a cost-effective, high-quality, and fast manufacturing approach for complexly shaped hollow fiber-reinforced composite materials. This challenge has recently been addressed and tackled in the EU funded *ambliFibre* project in which the main objective was to improve the diode laser-assisted tape winding process, systems, and assisting software solutions to enable efficient and flexible production of tubular composite parts. The role of the process simulation model in the *ambliFibre* project is illustrated in Figure 1.4.

The mission of *ambliFibre* was to develop and validate the first model-based laser-assisted tape winding system. This paves the road to achieve Industry 4.0 for automated composite manufacturing processes where the focus is on data-driven manufacturing and connecting the physical systems to digital twins. Within the *ambliFibre* project, two Ph.D. projects were defined towards numerical modeling of the LATW process:

i) Ph.D. 1: Developing a fast in-line local model for in-line process control to regulate the process temperature by continuously altering/adapting the process settings to their current optimum values.

ii) Ph.D. 2: Developing the off-line global modeling for a process design tool to accurately analyze the process temperature trends and to enable a priori virtual process optimization for new materials and products.

This thesis covers the first PhD project on developing numerical models for the LATW processes towards controlling the process which comprises two parts. Firstly, on the basis of the product geometry, its shape and dimensions, and the intended winding path of the tape, the amount of energy required to heat up the tape and substrate to maintain a nip point temperature within set limits can be determined in advance. Subsequently, fast inline control approaches are necessary to keep the nip point temperature within the required limits during the process to mitigate any inevitable variations in the process conditions. Unintended variations in tape velocity, mandrel dimensions, cooling conditions, etc. may interfere with the manufacturing process leading either directly or in course of time to unforeseen deviations in the nip point temperature.

1.4 State-of-the-art

Accurate control of the nip point temperature requires quantitative models that describe complex optical properties of the tape and the laser light. Although studies in the literature were performed to determine the optical properties e.g. in [6–10], the state-of-the-art optical models for the anisotropic reflection behavior of FRTP prepreg tapes still require comprehensive experimental characterization to determine the material parameters used in the optical models.

The process temperature monitoring, analysis, and modeling in the LATW or laser assisted tape placement (LATP) processes were broadly studied in the literature [11–18]. However, the reported analyses and modeling approaches were limited to *discontinuous* processing of FRP composites. Either only a single tape or layer of tapes is deposited on top of a substrate or after the deposition process sufficient waiting time is provided for the temperature to equilibrate with the environment before a next layer is deposited. In *continuous* winding no waiting time is included in the process and the actual substrate temperature may vary from place to place depending a.o. on the process conditions and placement/winding patterns. A generic physics-based model, capturing the underlying multi-physical phenomena, is required to describe and understand the *continuous* LATW processes, which has not been addressed in the literature so far. The analysis of the temperature variation in a *continuous* winding process, e.g. manufacturing of a pressure vessel, is necessary for the development of a robust processing.. Besides, the effects of various process parameters such as winding angle, pressure vessel size, etc. on the process temperature have not been pinpointed yet.

This is crucial in order to develop reliable and defect-free FRP composite parts manufactured by the LATW process. Despite the large amount of research on modeling and optimization of the LATW and LATP processes in the literature [19–24] no generic approach has been presented for complex curved surfaces such as the dome parts of pressure vessels to simulate and control the transient temperature behavior.

1.5 Objective and scope

The long term objective of this work is to achieve a robust LATW process by compensating the variability in the manufacturing process temperatures, resulting in repetitive and predictable part properties and performance. The work presented in this thesis takes the first steps towards the long term objective by developing the key building blocks. Five research objectives are defined for this purpose. Table 1.1 summarizes the objectives and their corresponding chapters.

Table 1.1 Objectives of the current thesis.

Chapter*	Objectives
2	To characterize optical parameters of prepreg tapes for accurate process modeling
3	To quantify the sources of temperature variation during a continuous LATW process
4	To accurately predict the process temperature evolution in adjacent hoop winding of pressure vessels
5	To identify the effect of winding angle, vessel diameter, and tape thickness on the laser intensity and temperature distributions
6	To optimize the LATW process with complex tooling geometries and variable curvatures

* Chapters are part of journal articles listed in section Publications.

1.6 Outline

The work performed in this thesis is centered around a number of research questions derived from the various objectives defined above. These questions are answered in the following chapters that are based on research papers that are either published or in preparation. In this way, each chapter can be read independently although some overlap from chapter to the chapter may exist, for which the author apologizes on beforehand.

The second chapter addresses the interaction of the laser light emitted by the laser source with the fibers embedded in the tape and substrate. A number of pre-impregnated tapes is characterized to understand the laser-tape and laser-substrate interactions. A generally applicable approach is provided to describe the non-homogeneous reflection of incident laser rays by the tape materials reinforced with glass or carbon fibers.

In Chapter 3 the LATW process is employed to wind three layers of prepreg tape in a *continuous* fashion on top of a thermoplastic liner as part of the manufacturing process of a full composite with a polymer liner, type IV-pressure vessel. The winding process of this type of vessel has been used throughout the remainder of the thesis as a representative example of an LATW process of a complex hollow product. This chapter provides an overview of the main phenomena typically occurring during *continuous* winding and it gives insight in the role of the various process parameters both in a qualitative as well as in a quantitative way.

The experimental results obtained in Chapter 3 are used as input for the comprehensive optical-thermal model that has been developed and validated in Chapter 4. The optical and thermal models established in this chapter are not only capable of predicting the temperature development in the tape and substrate as a function of place and time in advance. They are also designed in such a way that they can be applied at a later stage as part of inline control algorithms, to quickly update relevant process parameters to maintain the nip point temperature within set limits. Here, the emphasis is on the predicting capabilities of the models and an analysis of the observed sources of process variations is carried out.

The next chapter employs the developed and validated optical-thermal model to study the influence of several critical process variables such as the winding angle, the mandrel curvature and tape width on the nip point temperature. An in-depth study towards the relation among the provided laser power, the generated temperature distribution on the tape and substrate surfaces, and the related nip point temperature is carried out.

The next chapter employs the developed and validated optical-thermal model to study the influence of several critical process variables such as the winding angle, the mandrel curvature and tape width on the nip point temperature. An in-depth study is performed on the relation between the provided laser power, the resulting temperature distribution on the tape and substrate surfaces, and the corresponding nip point temperature.

In Chapter 6 the first steps towards optimization of the LATW process for continuous winding are made to study the effect of mandrel shape changes to the nip point temperature. Such a study is especially useful for more complex products that are characterized by shape and curvature variations. Here, the approach is applied to the cylindrical section and dome section of the pressure vessel studied in some of the previous chapters. Based on the obtained temperature development in each section, a new optimization strategy is developed to predict

the required total laser power to maintain the nip point temperature within set limits and thus safeguarding high-quality manufacturing of the part.

In Chapter 7 the results obtained from Chapters 2 to 6 are brought into a broader perspective. It discusses the status of the developed optical and thermal models in light of off-line and on-line process control. Based on this discussion, overall conclusions and recommendations for further research are provided in Chapter 8.

Chapter 2

Optical characterization of prepreg thermoplastic tapes

¹ The optical properties of unidirectional (UD) fiber reinforced thermoplastic (F RTP) tapes were characterized to enable a better description of the heating phase in laser-based manufacturing process of F RTP composites. The tapes included PP-GF (glass-fiber) 45% fiber volume content (FVC), PVDF-CF (carbon-fiber) 45% FVC, PVDF-CF 60% FVC and PA12-CF 60% FVC. The transmittance of the tapes was found to be 0.00%-0.2% whereas the reflectance was 9.8%-11.8% corresponding to a refractive index of 1.91-2.05. The anisotropic reflectance measurements, as obtained through a gonireflectometry, were used to fit the bidirectional reflectance distribution function (BRDF) for the first time. The obtained BRDF parameters σ_t and σ_f had a range of 0.1-0.18 and 0.006-0.015, respectively, for different tapes. Employing the new BRDF parameters empowers a more accurate prediction and optimization of the process settings of laser-based composite manufacturing.

2.1 Introduction

Laser-based composite manufacturing technologies such as laser assisted tape winding and placement (LATW/LATP) have become popular in producing fiber reinforced thermoplastic (F RTP) components with high strength-to-weight ratio. A rotating mandrel or liner is used in LATW whereas the tooling is stationary in LATP. A fully automated single step manufacturing can be achieved in LATW and LATP processes by the in-situ consolidation of the F RTP

¹This chapter was part of "A.Z., I.B., T.C.B., R.A., Optical characterization of fiber-reinforced thermoplastic tapes for laser-based composite manufacturing". A.Z. developed and performed the experiments and numerical simulations and wrote main structure of the paper, I.B. and T.C.B. provided critical review, commentary, and revision, R.A. contributed to the methodology and supervision of research.

prepreg tapes which can reduce the production costs and eliminate post consolidation or curing steps [25, 26]. A schematic view of a LATW process is depicted in Figure 2.1. The FRTP tapes are deposited onto a mandrel in an automated way using robotics.

The substrate and the tape are first irradiated by the laser light and then they are compressed at the nip point promoting in-situ consolidation. The optical properties of the materials, the extent of the irradiated areas on the tape and substrate surfaces and the degree of absorption and reflection of the laser light at these surfaces mainly determine the heating rate of the thermoplastic materials. The temperature at the nip point is often described as the process temperature which is regulated to control the consolidation quality and final mechanical properties of the FRTP composite parts [27, 28]. Accurate control of the nip point temperature requires quantitative models that describe the angle and material dependent absorption and reflection of laser light. For fiber based materials the interaction of the embedded fibers with the laser light is important as well. The matrix material surrounding the fibers is often relatively thin allowing a substantial amount of laser light to reach the fiber surface and interact at the fiber-matrix interface. In general the laser light can be reflected, absorbed and transmitted, where the reflection behavior can be specular (isotropic) and non-specular (anisotropic), depending on the optical properties of the UD thermoplastic tape and the incident angle, see also Figure 2.2, [29, 30].

Fig. 2.1 LATW process and emerging of the shadow.

The optical characterization of various FRTP prepreg tapes has been studied in literature. The transmittance of a carbon fiber reinforced polyether ether ketone (PEEK-CF) tapes with 55% fiber volume content (FVC) was characterized by employing an integrating sphere in [7]. The measured transmittance was found to be less than 0.1% for a laser light with a wavelength in the range of 500-2000 nm. Similarly, almost no transmittance was observed at a laser wavelength of 1060 nm in [8] for a carbon fiber reinforced PA6 (PA6-CF) prepreg tape with 49% FVC by using a spectrophotometer. The absorbance as a function of incident angle was quantified and approximately 90% absorptance (or 10% reflectance) of the tape was obtained for a zero degree incident angle. The absorptance dropped to approximately

Fig. 2.2 Incident laser light which is absorbed, transmitted and reflected by a FRTP tape. The reflection pattern can be specular, non-specular or combined specular and non-specular depending on the optical properties of the tape and the incident angle.

50% with an 85 degree incident angle. The surface reflectance of a unidirectional (UD) graphite/epoxy prepreg tape with 45% FVC was measured by using an infrared spectrometer in [31]. The total surface reflectance was found to be approximately 10% and 25% at 1000 nm and 5000 nm wavelength, respectively.

Besides the total reflectance measurements, the scattering patterns of the anisotropic reflection from FRTP tapes based on the fiber orientation were studied in [6, 7, 10, 32]. A single-lens reflex (SLR) camera was used to qualitatively characterize the reflections from UD carbon fiber reinforced polyphenylene sulfide (PPS-CF) tapes in [6] and PEEK-CF tapes in [7]. It was found that the diffusive reflection pattern varied significantly from a crescent like shape when the incoming laser light was aligned with the fiber orientation to a vertical line when the tapes were illuminated along the direction transverse to the fibers. The anisotropic reflection behavior was quantitatively analyzed in [10] for a PEEK-CF tape. The distribution of the bidirectional reflectivity was measured along the coplanar axis for different temperatures, fiber orientations and incident angles by using a Fourier transform infra-red spectrometer. The effect of temperature on the reflectivity of the FRTP tape was found to be negligible as compared with the effect of fiber orientation. The anisotropic reflection behavior of PA12-CF, PA6-GF and PVDF-CF tapes at room temperature and melt temperature was studied in [32] by using an SLR camera. The temperature had a more significant effect on the reflectivity of PA6-GF tapes than the reflectivity of PA12-CF and PVDF-CF tapes.

Optical models have been developed to predict the absorption and reflection behavior of FRTP tapes during the manufacturing process. The complex reflection behavior was approximated by employing only isotropic (specular) reflection patterns in the developed optical models in [33, 6, 34, 35]. The irradiated regions on the tape and substrate surfaces were described by using the ray tracing method. Recently, more comprehensive optical

models incorporating the anisotropic (non-specular) reflection behavior were developed in [7, 36, 30, 37]. The microstructure of a FRTP tape surface was defined by a number of microhalf cylinders and specular reflection was considered in [7, 36] by using the non-sequential ray tracing software (OptiCAD 10). The incident angle dependent reflectance was obtained by the Fresnel equations and a good approximation of the anisotropic scattering behavior of the composite was achieved. A three-dimensional (3D) non-specular reflection model was developed in [30, 37] by using the bidirectional reflectance distribution function (BRDF) [38]. The BRDF was formulated using the microfacet theory employed with the ray tracing approach. The non-specular scattering of the laser reflections was predicted for different fiber orientations and incident angles [39–41]. It was concluded that the parameters of the numerical optical model had significant influence on the anisotropic reflection patterns.

The state-of-the-art optical models presented in literature for the anisotropic reflection behavior of FRTP prepreg tapes still require comprehensive experimental characterization in order to determine the material parameters used in the models. This is necessary to develop accurate multi-physics based process models for laser-based manufacturing of composites to eliminate the trial-and-error based experimental approaches. The objective of this paper is therefore to characterize the optical properties of FRTP prepreg tapes with different FVC and correlate the model parameters in a numerical optical model incorporating the BRDF as presented in [30] for the anisotropic reflection distribution. Four different FRTP tapes are studied namely CF reinforced polyamide 12 (PA12-CF) 60% FVC, GF reinforced polypropylene (PP-GF) 45% FVC, CF reinforced polyvinylidene fluoride (PVDF-CF) 45% and 60% FVC.

The paper is built up as follows. First, the microstructure and surface roughness of the tapes are analyzed. Afterward, the total transmittance and reflectance are determined by using a power meter and an integrating sphere. Then, the refractive indices of the four different tapes are calculated with the help of the Fresnel equations. The anisotropic reflection patterns with different fiber orientations are studied by employing a gonireflectometer. The optical model parameters are determined by fitting the predicted reflection patterns with the measured ones. The experimental work is described in Section 2. The anisotropic reflection modeling using the BRDF and fitting procedure are explained in Section 3. The obtained results are presented and discussed in Section 4. Section 5 gives an overview of the conclusions and future outlook in the field of optical characterization and modeling for the FRTP tapes.

2.2 Experimental

2.2.1 Materials (microscopy)

The materials used in this work were the UD PA12-CF with 60% FVC, PP-GF with 45% FVC, PVDF-CF (A) 60% FVC and PVDF-CF (B) 45% FVC which are shown in Figure 2.3 with the corresponding width and thickness (Δ) of the tapes. The PA12-CF and PP-GF tapes were supplied by Celanese and the two PVDF-CF tapes were supplied by Baker Hughes, a GE company. The thickness of PA12-CF and PVDF-CF (A) tapes was 0.15 mm whereas it was 0.25 mm for PP-GF and PVDF-CF (B) tapes. Note, that the PP-GF tape was black-pigmented in order to enhance the absorption.

Fig. 2.3 Utilized UD FRTP tapes and the corresponding properties including width, thickness and FVC.

The quantitative optical property differences among the investigated tapes were the point of interest as the optical responses received from the tape surfaces might be varied due to the irregular fiber distribution and the interaction of laser rays with the tape surface. Therefore, the microstructures of the tapes were analyzed by using an optical light microscopy and the surface roughness was quantified by using a confocal microscopy.

The as-received UD tapes were cut, embedded in epoxy and polished for cross-sectional microscopy purposes in order to observe the distribution of fibers across the thickness. The Keyence VHX-5000 digital microscope was used to obtain high contrast cross-sectional images. The exemplary cross-sections obtained from the microscope are shown in Figure 2.4. It is seen that the fibers were uniformly distributed and located near the surface for the PA12-CF and PVDF-CF (A). However, the fibers were less uniformly distributed over the cross-section for the PP-GF and PVDF-CF (B) and the tapes contained resin rich regions.

Moreover, there were less fibers located near the surface which might influence the reflection behavior.

Fig. 2.4 Micrographs of the tape cross-sections and magnified fibers across the thickness (Δ).

The surface topology and roughness of the as-received tapes were analyzed by using the laser scanning confocal microscope Keyence VK-X1050. Figure 2.5 shows the micrographs of the tape surfaces and the corresponding average and root mean square (Ra and RMS) of the surface roughness. The presence of the fibers was visible for the PVDF-CF (A), black-pigmented PP-GF and PA12-CF tapes as seen in Figure 2.5(a). However, most of the surface of the PVDF-CF (B) tape was occupied by the polymer matrix as can be seen also from Figure 2.4 (see "resin rich"). Although both PP-GF and PVDF-CF (B) had 45% FVC and a thickness of 0.25 mm, the fiber distribution near the surface was different probably due to differences in the tape manufacturing process. In addition, the presence of surface anomalies like voids and fiber misalignments was observed in Figure 2.5 for all UD tapes which might change the local refractive index (absorption) and anisotropic reflection behavior. According to the measured surface roughness parameters as seen in Figure 2.5(b), PA12-CF and PP-GF tapes had the smallest Ra value as approximately $5 \mu\text{m}$ and RMS value as approximately $6 \mu\text{m}$. On the other hand, PVDF-CF (A) and PVDF-CF (B) tapes had larger Ra and RMS values approximately as $12 \mu\text{m}$ and $16 \mu\text{m}$, respectively.

2.2.2 Transmittance and reflectance measurements

The total transmittance was measured by using two techniques including a power meter as a direct method and an integrating sphere as a diffusive method. The integrating sphere

(a)

(b)

Fig. 2.5 (a) Micrograph of the tape surfaces obtained by the confocal microscopy. The fiber misalignments, surface anomalies and voids indicated with dashed circles can be observed differently for the tapes. (b) The measured average (Ra) and root mean square (RMS) of the surface roughness.

was also employed for the measurement of the total reflectance albeit with a different setup. The direct measurement of the transmittance was performed by placing a power meter on the backside of the tape as shown in Figure 2.6(a)(left). The samples were put in front of the integrating sphere as shown in Figure 2.6(a)(right) for the diffusive transmittance measurement. A portion of the laser energy passes into the integrating sphere and it bounces until it is detected by the detector. The total reflectance was measured by putting the UD tape samples on the backside of the integrating sphere as schematically seen in Figure 2.6 (b). The laser light goes inside the integrating sphere, where it hits the sample and then a

portion of the laser light is reflected from the tape surface. The laser light bounces in the highly reflective sphere until it is detected by the sensor. The reflection behavior at the tape surface depends on the local surface roughness and the fiber orientation. However, the total reflected energy obtained within the integrating sphere remains the same for a given tape material independent of the local surface roughness of the tape. Differences in the tape matrix material and the FVC are expected to lead to differences in the total reflectance from tape to tape.

The refractive indices of the tapes were calculated by using Snell's Law and the Fresnel equations [42] based on the measured values of the tape reflectance from the diffusive method. The determined indices were validated by measuring the reflectance of a PEEK-CF tape with 60% FVC with a known reflective index and a measured *RMS* value of the tape surface, $n_{PEEK-CF}(60\%) = 1.95$ and $RMS = 2.2$, respectively [28].

The employed experimental setups for the optical measurements described in Figure 2.6 were provided by the Chair of Laser Processing at the University of Twente. A CPS980S Thorlabs collimated slim laser module with a typical center wavelength close to 980 nm was employed as the laser source for the direct transmittance measurements similar to the operating laser in the LATW and LATP processes. It featured an elliptical beam shape with a size of $3.8 \text{ mm} \times 1.8 \text{ mm}$. The maximum power of the laser was 5 mW with 1.5 mrad as the maximum beam divergence. The power meter was a Thorlabs S130C with a wavelength range of 200-1100 nm and a power range 500 pW-5 mW. The detector type was a Si photodiode with a measurement uncertainty of $\pm 3\%$.

The main parts of the integrating sphere include a broadband light source (300-2500 nm) from AvaLight-HAL-S of Avantes, an HR-4000 spectrometer from Ocean Optics and a UPB-150-ART highly reflective integrating sphere from Gigahertz-Optik. The laser light was guided by fiber optic from the light source toward the integrating sphere. The laser light was focused by an achromatic doublet lens on the UD tape sample. The reflection spectrum obtained from the detector as collected by the spectrometer [43]. It was only possible for perpendicular irradiation on the sample measured (roughly 89.9° between laser ray and surface tangent) since only tiny holes available on the sides of the integrating sphere were used (holes for laser source, UD tape sample and detector). The integrating sphere was stabilized by running it for about 15 minutes at the beginning of experiments.

2.2.3 Anisotropic reflection measurement

Gonioreflectometer measurements can be carried out to study the reflection intensity distribution from non-homogeneous surfaces [44, 10] such as the tapes considered in this work. The measurements are key in understanding the complex relation between the fiber orientation,

Fig. 2.6 Schematic of the experimental measurements of the total (a) transmittance and (b) reflectance. The total transmittance was measured using both the power meter (direct approach) and the integrating sphere (diffusive approach). The total reflectance was measured only via the integrating sphere.

the direction of the incident laser beam and the resulting non-specular reflection pattern. The measurement approach is schematically shown in Figure 2.7. A fixed sample is irradiated by a stationary laser where the incident laser beam has a constant inclination angle α with the specimen normal vector. The reflected intensity is measured with a detector that covers a hemisphere around the sample. The origin of the hemisphere coincides with the location where the laser irradiates the sample. The geometrical location of the detector can be given in terms of its longitude ϕ_C and latitude ϕ_S .

The measurements were performed with the gonireflectometer available at Fraunhofer ILT (Aachen). It uses a CPS980S Thorlabs laser source and an SFH 229FA photodiode from Osram with a wavelength of 730 nm-1100 nm to measure the reflected intensity. The laser beam angle with respect to the irradiating surface horizontal line (β) was 33, i.e. incident angle $\alpha = 57$, as seen in Figure 2.7. The small misalignment of samples occurred during the adjustment procedure which was roughly 2-3°. The hemisphere is characterized by a radius of 488.4 mm which equals the distance from the detector to the laser spot on the sample surface. The complete hemisphere is scanned in steps of $\Delta\phi_C = \Delta\phi_S = 0.05$ degrees to capture a sufficient density of measurement points. After the reflection measurements, which typically took 2-3 hours, the sample was rotated manually and the reflection measurements were

repeated. The following fiber orientations were considered: 0, 10, 25, 40, 60, 80 and 90. The gonireflectometer was kept in a dark chamber during the experiments to reduce the noise coming from the ambient light. In addition to the prepreg tapes, a highly reflective mirror with 99.9% reflection was employed in the gonireflectometer experiments to compare the mirror-like reflection patterns with the anisotropic reflection of the prepreg tapes.

Fig. 2.7 Employed gonireflectometer setup from Fraunhofer ILT for measuring the spatial distribution of diffusive reflectance from UD tapes. The main elements of the gonireflectometer include C-arm, sensor saddle, laser pointer, UD tape sample and laser source beam. The sensor saddle moves along the C-arm to collect reflected light information for each rotation of the C-arm. The laser beam irradiates the sample with $\beta=33$ (incident angle $\alpha=57$) where $\vec{n}$ is the normal vector.

2.3 Anisotropic reflection modeling

The BRDF modeling approach was employed to mathematically capture the anisotropic reflection distributions of the FRTP tapes. The utilized BRDF in this paper was developed and described in detail in [30]. The BRDF simulation made a relation between the incoming ray and the reflected rays based on the micro-facet distribution representing the effect of fibers on the diffusive reflection. An anisotropic Gaussian distribution in spherical coordinates was employed for the the micro-facet distribution $p(\hat{h})$ as described in Equation 2.1:

$$p(\hat{h}) = p(\phi_s, \phi_c) = \exp\left(-\tan^2 \phi_s \left(\frac{\cos^2(\phi_c)}{2\sigma_f^2} + \frac{\sin^2(\phi_c)}{2\sigma_t^2}\right)\right) \quad (2.1)$$

In Equation 2.1, $\hat{h}$ is the normal of each micro-facet defined by ϕ_S as the latitude angle and ϕ_C as the longitude angle, σ_f and σ_t are the BRDF parameters describing the Gaussian function intensity along ϕ_S and ϕ_C , respectively. Here, the anisotropic distribution of the micro-facet normal allows to control the size of the spread in the fiber and transverse to the fiber directions. The reflected BRDF rays are constructed as they specularly reflected from the micro-facets. Based on the relative fiber orientation and incident angles different reflection pattern can be obtained.

An illustration of the anisotropic reflection behavior from a virtual UD prepreg tape using the Gaussian BRDF model is presented with $\sigma_f=0.1$ and $\sigma_t=0.2$ and 0.5 in Figure 2.8. The left side of the figure explains the relation between the laser light direction, the micro-facet based reflection at the fiber surface and the obtained projected intensity distributions. The right side of the figure shows the obtained intensity distributions as virtually recorded by the detector on the hemisphere about the sample. In the left part of the figure the fiber orientation is given in terms of a local coordinate system $\hat{e}_f$, $\hat{e}_t$ and $\hat{e}_n$ which are the directions along the fiber, transverse to the fiber and normal to the fibers micro-facet surface, respectively. The angles α and ϕ were defined in Figure 2.7. The intensity distributions shown in Figure 2.8 were obtained for $\alpha = 60$ with $\phi = 0, 45$ and 90 .

The illustrated micro-facet distributions are mainly along the transverse direction in the spherical coordinate system, i.e. $\hat{e}_t$, since σ_t is larger than σ_f in this figure. The micro-facet behavior was shown through changing of σ_t from 0.2 to 0.5 to cause a bigger spread of the micro facets along $\hat{e}_t$ which causes a corresponding broadening effect on the reflection patterns in Figure 2.8. Every facet has a different normal vector with respect to the incoming ray. Therefore, the effect of the fiber orientation was included inherently using the micro-facet distribution. A uniform sampling of reflected rays was employed for the analysis in this paper as carried out in [30].

The BRDF parameters σ_f and σ_t of the various tapes used in LATW and LATP processes are not known on beforehand as mentioned earlier in the introduction section. Therefore, the anisotropic reflection patterns obtained from the BRDF simulations were fit to the reflection behavior observed in the gonireflectometer measurements via adjusting σ_f and σ_t for each F RTP tape used in this work.

The variables for the fitting procedure, D_x and D_y , are oriented along the ϕ_C and ϕ_S axes, respectively. The measured intensity distribution is projected on a plane in the same way as shown schematically in Figure 2.8. An example of such a projection is shown in Figure 2.9. Here, D_x is defined as the distance between the left and right edge of the reflection pattern in ϕ_C direction and D_y is the distance between the upper and lower edge at the centerline of the reflection pattern in ϕ_S direction. A higher value of σ_f and σ_t generates a larger spread of

Fig. 2.8 Virtual reflectance pattern from a UD prepreg tape using the BRDF model for different BRDF parameters ($\alpha=60$, $\sigma_f=0.1$, $\sigma_t=0.2$ and 0.5) and fiber orientations ($\phi=0$, 45 and 90). The local coordinate system of the tape includes $\hat{e}_f$ as along fiber direction, $\hat{e}_t$ as the transverse direction with respect to the fibers and $\hat{e}_n$ as the normal of the sample surface.

the reflected rays along the ϕ_S and ϕ_C directions, respectively. Once σ_f and σ_t were found for each FRTP tape at $\phi = 0$, the intensity distributions for the other fiber orientation angles were predicted by using the same values of σ_f and σ_t . Subsequently, the simulated intensity distributions were compared with the respective experimental gonireflectometer results for the other fiber orientation angles. In all experiments the laser incident angle was exercised at 57° .

2.4 Results and discussions

2.4.1 Experimental

Transmittance and reflectance

The total transmittance, reflectance and calculated refractive index of the tapes are presented in Table 2.1. Overall, the transmittance as determined with the power meter and the integrating sphere methods is negligibly small. The measured maximum average transmittance was 0.2% of the initial energy for the black-pigmented PP-GF and was found to be less than 0.01% of the initial energy for other CF-based UD tapes. Although the tapes had different thicknesses that might affect the transmittance, it was observed that the thickness difference among the tapes played a negligible role as the PEEK-CF and PA12-CF tapes with $\Delta=0.15$

Fig. 2.9 Schematic view of the reflected light for $\phi=0$. The fitting procedure to determine σ_t and σ_f which control the amount of widening (in degree) is defined based on latitude as D_y and longitude as D_x of the reflected light. The distance between the left and right edge of the pattern denoted as D_x and the distance between the upper and bottom part denoted as D_y at the center are calculated. The intensity distribution is scaled to its maximum value.

mm had 0 transmittance. On the other hand, the PVDF-CF (B) and PP-GF with $\Delta=0.25$ mm had a slight transmittance. The relatively non-uniform fiber distribution, e.g. for PVDF-CF tapes as compared to PA12-CF (see fiber distribution Figure 2.4), was the reason for a small amount of transmitted radiation in the CF-based tapes as CFs blocks the laser transmission through the tapes [45].

Table 2.1 Measured transmittance (direct and diffusive methods), reflectance (diffusive method), and corresponding refractive index of the employed UD thermoplastic tapes.

UD tapes	PEEK-CF	PA12-CF	PP-GF	PVDF-CF(A)	PVDF-CF(B)
FVC [%]	60	60	45	60	45
Transmittance [%]	0.00 ± 0.000	0.00 ± 0.000	0.2 ± 0.1	0.010 ± 0.003	0.005 ± 0.005
Total reflectance [%]	10.5 ± 0.25	11.8 ± 0.3	9.8 ± 1.4	11.6 ± 0.9	10.3 ± 1.8
Mean refractive index	1.96	2.05	1.91	2.03	1.94

The total reflectance values from the UD tapes were found to be very close to each other varying between 9.8% to 11.8% as seen in Table 2.1. The refractive indices of the tapes were found to be between 1.91 and 2.05 by incorporating the measured total reflectance in the Fresnel equation for 0 degree incident angle. The refractive index of PEEK-CF was studied in order to verify/validate the total reflectance measurements with the literature. A very good agreement was obtained for the refractive index of PEEK-CF between the reported value of approximately 1.95 in [46] and [36] and the current finding which was 1.96.

The mean value of the total reflectance for PVDF-CF (A) was found to be approximately 1.3% larger than the reflectance of PVDF-CF(B) although both materials comprise the same fiber and matrix. It was ascribed to the higher FVC of PVDF-CF(A), where it is known that fibers are the main source of the reflective behavior. The variation in reflectance behavior

among the various UD tapes seems to have a direct relation with the homogeneity of the fiber distributions as displayed earlier in Figure 2.4 and the presence of surface anomalies, such as voids and fiber misalignments, shown in Figure 2.5. The PVDF-CF (B) 45% FVC tape demonstrated a relatively large variation in the reflectance, equal to 1.8 % on an average value of 10.3 %, which corresponds with the strongest non-uniformity of the fiber distribution. On the contrary, a more homogeneous fiber distribution with fewer surface anomalies and presence of fibers near the surface resulted in a relatively small reflectance variation equal to approximately 0.3% for PA12-CF and 0.25% for PEEK-CF with 60% FVC on average values of 11.8% and 10.5%, respectively. In case of PP-GF the determined value of the refractive index may seem too high with a value of 1.91, where the typical refractive index of polymers is reported between 1.4-1.6 [47] and the refractive index of GF is approximately equal to 1.5 [48]. However, this material is filled with additional black pigments clearly resulting in an increase in the laser absorption leading to a comparatively higher refractive index. Finally, it can be observed that the FVC seems to be related to the refractive index as higher FVCs typically increase the corresponding values of the refractive index.

Anisotropic reflection

The normalized intensity distributions of the laser reflections from the UD tapes with $\phi=0$ as well as from the highly reflective mirror are shown in Figure 2.10. Each intensity distribution in Figure 2.10 was normalized with its maximum value. The latitude angle was almost the same for each tape at approximately 57 ± 3 and the center of the crescent shapes was located almost at a longitude of approximately 0 ± 2 . It is seen that the laser reflections from the mirror were almost isotropic and occupied approximately 2 degrees in the latitude and longitude directions based on the spherical coordinates. On the other hand, the anisotropic reflections from the UD tapes covered a larger area in the longitude and latitude directions. The differences among the reflection intensity distribution shapes for the UD tapes are due to the different fiber distribution, FVC, fiber size and surface anomalies as observed before. In other words, the penetration of the laser light into the matrix and interaction with fibers inside the media of the UD tape occurs which subsequently causes different intensity distributions of the reflection light. The results of PA12-CF and PVDF-CF(A) with 60% FVC had a very similar reflection intensity shape as seen in Figure 2.10 where a crescent reflection from cylindrical fibers fibers, as simulated and shown in Figure 2.8 and Figure 2.9, was neatly captured. Both PVDF-CF(B) and PP-GF with 45% FVC on the other hand showed a less crescent-like intensity distribution shape. Small reflection intensity irregularities of the PVDF-CF(B) sample were related to the non-homogeneous fiber distribution across the thickness as seen in Figure 2.4. The bigger size of the GFs compared to the CFs was another

important point which caused differences in the radiative properties between PP-GF tape and the CF-based tapes.

Fig. 2.10 Normalized reflectance intensity distributions of the employed UD tapes at zero orientation of fibers ($\phi=0$) and the mirror case obtained through the gonireflectometer experiments.

The normalized anisotropic reflection intensity distribution results of different fiber orientations of the PA12-CF tape from $\phi=10$ to $\phi=90$ are shown in Figure 2.11. The measured intensity distributions rotated by increasing the fiber orientation and became slightly slender for $\phi=90$. In addition, the length of the scatter in the latitude direction increased as the fiber orientation was increased from $\phi=0$ to $\phi=90$. The left edge of the crescent shape in Figure 2.11 moved from -70 to -85 in the latitude direction, and the right edge moved from -65 to -20 in the latitude direction for $\phi=10$ to $\phi=90$. Similarly, two edges of crescent reflections moved from -15 and 20 to 0 in the longitude direction for $\phi=10$ to $\phi=90$. The change in shape and orientation of the reflected intensity distributions is mostly related to the change in the laser irradiation direction (incident angle) on the cylindrical fibers at micro-level. A more detailed

explanation of the relation for laser irradiated cylindrical fibers can be found in [7]. Hence, the length of the reflection pattern in the latitude and longitude directions was driven by the fiber orientation. The trend of fiber orientation effect on the reflected intensity distributions was the same for all UD tapes as it was a geometrical effect. However, detailed differences may occur in the reflected intensity distributions from tape to tape and even for different fiber orientation angles for a single tape due to the non-uniformity of the fiber distributions and/or the presence of local anomalies, as studied earlier and shown in Figure 2.4.

Fig. 2.11 Normalized reflectance intensity distribution of the PA12-CF tape at different orientation of fibers ($\phi=10-90$) via the gonireflectometer experiments.

The background noise (approximately 0.1%) of the normalized reflected intensity distributions were removed to prepare the measurements for the fitting procedure based on the BRDF model. An example of a 3D reflected intensity distribution with the determined dimensions in longitude (D_x) and latitude direction (D_y) is shown for PA 12-CF at $\phi=0$ in Figure 2.12. In this case, D_x is 56 and D_y is 16. The widening parameters of other samples are listed in Table 2.2. The values of D_x from the tape samples were approximately 14 to 24 times larger than the mirror sample. The widening values determined by D_y for tapes were smaller than D_x , where they were approximately 4-9 times larger than the mirror case result.

Table 2.2 Widening parameters (D_x and D_y) of the mirror (source) and employed UD tapes at zero orientation of fibers ($\phi=0$) after removing the background noise.

Sample FVC [%]	Mirror	PA12-CF	PP-GF	PVDF-CF(A)	PVDF-CF(B)	Unit
	-	60	45	60	45	-
D_x	2.9	56	42	68	47	[°]
D_y	2.3	16	21	9.5	18	[°]

Fig. 2.12 3D representation of the measured normalized reflectance distribution of the PA12-CF UD tape at zero orientation of fibers ($\phi=0$) as obtained through the gonireflectometer experiment and corrected for background noise. The widening parameters (D_x and D_y) of the captured shape are estimated after removing the background noise.

2.4.2 Modeling

The developed optical model using the BRDF was first used to investigate the effect of σ_t and σ_f on D_x and D_y for the anisotropic reflection pattern for $\phi=0$ and $\alpha=57$. Figure 2.13 shows the sensitivity of D_x to σ_t and of D_y to σ_f . The shape of the profiles was highly dependent on the incident angle where α was 57. For smaller values of σ_t and σ_f ($\sigma_t < 0.2$ and $\sigma_f < 0.05$) the dimensions (D_x and D_y) of the anisotropic reflections (crescent shapes) for $\phi=0$ were found to vary almost linearly. The parameters D_x and D_y rose to approximately 75 and 55, respectively, then the slope of the profiles became gradually flatter. Based on the measured dimensions of the crescent shapes (D_x and D_y) in Table 2.2, a region of interest about the experimentally observed dimensions was determined first, which was 0-0.2 for σ_t and 0-0.1 for σ_f . Afterward, σ_t and σ_f were fitted to the measured values of D_x and D_y by using a brute-force search algorithm.

The obtained values of σ_t and σ_f are given in Table 2.3 for each UD tape investigated in this work. Here, the anisotropic reflection simulations were denoted as Vir-1, Vir-2, Vir-3 and Vir-4 for PA12-CF, PP-GF, PVDF-CF(A) and PVDF-CF(B), respectively. The σ_t had a range between 0.1 to 0.18, whereas σ_f was between 0.006 to 0.015. The obtained BRDF parameters were much smaller than the default BRDF values ($\sigma_t=0.5$ and $\sigma_f=0.05$) employed in [30] where the numerical BRDF model was introduced without any optical

material characterization. It was observed that the PA12-CF and PVDF-CF(A) tapes with 60% FVC had higher values of σ_t and smaller values of σ_f than the corresponding values from the PP-GF and PVDF-CF(B) with 45% FVC as seen in Table 2.3. Therefore, a larger FVC resulted in more spread of the reflected laser rays along the longitudinal axis (more dominant crescent reflection shape) at $\phi=0$.

Fig. 2.13 The change in the size of the reflection pattern (crescent shape) as a function of BRDF model parameters, (a) σ_t and (b) σ_f , at zero orientation of fibers ($\phi=0$) for $\alpha=57$.

Table 2.3 Calculated BRDF parameters for the employed UD thermoplastic tapes based on the measured widening in Table 2.2 at zero orientation of fibers ($\phi=0$).

Simulations FVC [%]	PA12-CF (Vir-1) 60	PP-GF (Vir-2) 45	PVDF-CF(A) (Vir-3) 60	PVDF-CF(B) (Vir-4) 45
σ_f	0.01	0.015	0.006	0.012
σ_t	0.15	0.10	0.18	0.12

The fitted values of the BRDF parameters seen in Table 2.3 were employed in the anisotropic reflection BRDF model to generate hemispherical reflections for $\phi=0$. The estimated reflection intensity distribution based on the fitted σ_t and σ_f , and the borders of the experimentally and numerically obtained reflection patterns for $\phi=0$ are shown in the spherical coordinate system along the longitude and latitude directions in Figure 2.14. The tails of the experimental borders were outside the measurement area and were extrapolated in order to make a comparison with the model predictions.

Very similar reflection intensities and borders were obtained from the simulations as compared with the measurements. In fact, the anisotropic reflection model was very well capable in general to capture the different crescent-shaped patterns for the UD tapes employed. The measured reflection patterns had local variations which could be related to the non-uniform fiber distributions (e.g. PVDF-CF (B)), possible slight misalignment of the sample with respect to the laser source, local surface anomalies. There was no correlation found

Fig. 2.14 The extracted experimental and BRDF simulation reflection borders for tape samples at zero orientation of fibers ($\phi=0$) for the obtained parameters in Table 2.3. Non-measured areas in the gonioreflectometer experiments were recreated (post-processed) for some cases based on their curved slope to estimate their widening.

between the surface roughness of the UD tapes (Ra and RMS values) and the reflection patterns for $\phi=0$. This indicates that the anisotropic (diffusive) reflection behavior is highly driven by the fibers and their configuration.

The predicted reflection patterns in spherical coordinates for different fiber orientations by using the determined σ_t and σ_f at $\phi=0$ are shown in Figure 2.15 for PA12-CF. The PA12-CF results are representative for the results of all tapes employed in this work. Here, the comparison between the experimental and numerical anisotropic reflection patterns for $\phi= 10, 25, 40, 60, 80$ and 90 are displayed. The simulated/ modeled BRDF reflection intensities are shown as contour plot in the top left of each subfigure and borders are shown in blue for the BRDF and in black for the experiments. Although some part of the experimental borders was outside of the measurement region, the predicted and measured shapes matched overall well. The development of the shape of the reflected intensity distributions is similar to developments observed with the simulated BRDF patterns. Nevertheless, the tails of the predicted reflection patterns for $\phi= 40, 60$ and 80 deviated somewhat from the measured reflection patterns. Possible reasons explaining the observed differences include the predefined micro-facet distributions used in the BRDF model which did not take the actual fiber distribution into

account and the aforementioned measurement errors together with the irregularities in the micro-structure of the UD tapes.

Fig. 2.15 Predicted and measured reflection intensity borders along the longitude and latitude axes for (a) $\phi=10^\circ$, (b) $\phi=25^\circ$, (c) $\phi=40^\circ$, (d) $\phi=60^\circ$, (e) $\phi=80^\circ$ and (f) $\phi=90^\circ$ of the employed PA12-CF UD tape. The small scales of the BRDF intensity distribution of each case are also shown in the pictures.

2.5 Conclusions and future outlook

The optical characterization of several UD thermoplastic tapes was conducted as the optical behavior plays an important role for accurate temperature prediction in laser-based FRTP composite manufacturing processes. The characterization was performed to determine the

transmittance and reflectance behavior of a number of typical thermoplastic tapes, including PA12-CF 60%FVC, PP-GF 45%FVC, PVDF-CF 45%FVC, and PVDF-CF 60%FVC. The total transmittance was measured using a power meter as a direct approach and an integrating sphere as a diffusive approach, whereas the total reflectance was measured using only the integrating sphere. In these experiments the PEEK-CF 60%FVC prepreg was employed as the reference sample.

The total transmittance of the UD thermoplastic tapes ranged from negligibly small to very small values of 0.2% of the supplied laser energy. The total mean reflectance varied between 9.8% to 11.8% corresponding to a refractive index of 1.91 to 2.05. The total reflectance and the variation of this value were mostly influenced by the FVC and the type of fiber (glass vs carbon fiber). At higher values of the FVC the total reflectance increased (for example: PVDF-CF with 45% and 60% FVC) and the variation about the mean value decreased.

Goniorelectometry was employed to study more in depth the anisotropic reflectance behavior related to the alignment of fibers within the UD tapes. When the fibers were aligned parallel to the projected incoming laser direction on the tape plane ($\phi = 0$) a crescent reflection intensity distribution resulted, whereas increasing the misalignment (increasing ϕ from 0 to 90) resulted in a more straight and slender reflected intensity distribution. The shape and width of the generated patterns differed strongly from that of a mirror type of reference sample. The UD tape based reflectance behavior was mostly influenced by the FVC, the uniformity of the fiber distribution and the presence of surface anomalies rather than the surface roughness as characterized by Ra and RMS values. Higher fiber volume contents typically intensified the crescent like shape of the reflected intensity distribution.

The implemented optical BRDF model as a computational platform successfully enabled capturing the anisotropic reflections as observed in the experiments where tapes with a higher FVC provided higher values of σ_t and smaller values of σ_f . The obtained BRDF parameters σ_t and σ_f had a range of 0.1-0.18 and 0.006-0.015, respectively, for different tapes. The new BRDF parameters were found to be smaller than the ones used in the literature before in [30] which gives a new contribution toward developing an accurate optical model for these types of tapes. The intrinsic BRDF parameters obtained from the 0 fiber orientation could satisfactorily capture the reflected intensity distributions of other orientations (10 - 90), but some discrepancies existed related to irregularities in the fiber distribution, non-perfect Gaussian laser source, surface anomalies and possible metrology errors.

The described anisotropic reflection implies the need for a careful consideration of the selected materials (including FVC and fiber distribution) in the designing phase of high-quality composite part manufacturing processes, such as LATW and LATP. Utilizing the

new BRDF parameters in the optical process model empowers the computational tool to accurately predict and optimize the process settings of laser-based composite manufacturing processes. Further developments including a more comprehensive statistical description for the BRDF model and incorporating temperature dependency of the tape reflectance behavior into the model are reserved as parts of future works.

Chapter 3

Variation in process temperature in continuous LATW

¹ Laser assisted tape winding (LATW) is an automated process to produce tubular or tube-like continuous fiber-reinforced polymer composites by winding a tape around a mandrel or liner. Placing additional layers on a previously heated substrate and variation in material and process parameters cause a variation in the bonding temperature of fiber reinforced thermoplastic tapes which needs to be understood and described well in order to have a reliable manufacturing process. In order to quantify the variation in this critical bonding temperature, a comprehensive temperature analysis of an adjacent hoop winding process of type-IV pressure vessels is performed. A total of five tanks are manufactured in which three glass/HDPE tapes are placed on an HDPE liner. The tape and substrate temperatures, roller force and tape feeding velocity are measured. The coefficient of variation (COV) for each round is characterized for the first time. According to the statistical analysis, the COV in substrate temperature is found to be approximately 4.8-8.8 % which is larger than the COV of the tape temperature which is 2.1-7.8 %. The COVs of the substrate temperatures in the third round decrease as compared with the COVs in the second round mainly due to the change in gap/overlap behavior of the deposited tapes. Fourier and thermographic analysis evince that the geometrical disturbances such as unroundness and eccentricity have a direct effect on the temperature variation.

¹This chapter was part of "A.Z., M.S., I.B., T.C.B., H.J. and R.A., Temperature variation during continuous laser-assisted adjacent hoop winding of type-IV pressure vessels: An experimental analysis, Journal of composite materials. 2019 Nov, DOI.org/10.1177/0021998319884101". A.Z. developed and performed analysis methods and wrote main structure of the paper, M.S. performed experiments, I.B. and T.C.B. provided critical review, H.J. contributed to the methodology and R.A. contributed to the methodology and supervision of research.

In addition to the temperature feedback control, a real-time object detection techniques with deep learning algorithms can be used to mitigate the unwanted temperature variation and to have a more reliable thermal history.

3.1 Introduction

New fuel regulations and emission restrictions in the transport sector increase the appeal of lightweight composite components. Especially, thermoplastic composites experience a rise in applications due to their unique characteristics, including repeated shapeability and recyclability [49]. Manufacturing of sustainable products with respect to challenging environmental influences, quick adaptability, failure-free quality and safe operation over the complete life cycle is mandatory. The lightweight components like composite pressure vessels for the storage of hydrogen [50] or compressed natural gas (CNG) are gaining appeal within the automotive and transport industries [49]. Pressure vessels with a full composite design (type IV- an all-composite construction featuring a polymer liner with carbon or glass fiber reinforcement) exhibit relatively high specific strength and rigidity as well as corrosion resistance [51, 52]. The combination of a thermoplastic liner with composite reinforcements to substitute conventional metal designs enables relatively high internal gas pressures, which together with the reduced pressure vessel weight adds to the range (longer distance) of fuel-cell based or CNG applications [53]. For this type of lightweight pressure vessels, HDPE (high-density polyethylene) is often selected as a durable solid material which can dampen and absorb shock waves minimizing surges as well as the abrasion resistance. This polymer material is well-suited for industrial, automotive and sporting goods applications where cost and processability are critical [54–56]. Regarding the reinforcement tapes, glass fiber (GF)-reinforced tape is preferred for low-pressure applications rather than carbon fiber (CF) tapes due to pricing, higher durability and more mechanical flexibility (carbon fibers are more rigid) [57]. Thus, the manufacturing of glass fiber-reinforced type-IV pressure vessels is highly favored in high-volume applications, where low unit cost is a priority.

One of the advanced techniques to make tubular long or continuous fiber-reinforced thermoplastic (CFRTs) components like pressure vessels is laser-assisted tape winding (LATW) [58]. LATW has been a source of great interest to attain higher composite part accuracy and quality but with reduced cycle times. The LATW process relies on heating through diode lasers similar to laser-assisted tape placement (LATP). These diode lasers are preferred over alternative heating sources, e.g. hot gas or infrared emitters, due to their high energy concentration, short response times and excellent controllability for ensuring an ideal heat input adapted to the current process velocity [58, 59]. Another advantage of

the LATW process is avoiding additional curing steps which makes it more time-efficient in comparison with competing thermoset composite manufacturing technologies [60]. This is achieved via in-situ consolidation of the thermoplastic unidirectional fiber-reinforced tape and the substrate, which are simultaneously heated by a focused laser spot in the process zone while the pressure is applied to the substrate surface and the tape simultaneously.

In Figure 5.1, a typical hoop-winding case is shown where the tape and substrate are heated by the laser source on a cylindrical liner. The winding path in a continuous LATW process is designed such that it includes transitions between different angles in subsequent layers. The process can be used for the manufacturing of either concluded products like pressure vessels or continuous ones like pipes for oil and gas recovery in offshore deep-sea applications depending on the actuating system technology guiding the tape winding head [61].

Fig. 3.1 Description of the LATW elements including laser optics, substrate, tape, roller, and liner. The hoop-winding process where thermoplastic tape and substrate are preheated by the laser source and the tape is pressed on the substrate at the nip-point location through a consolidation roller are shown as: (a) Principle and (b) System technology (detailed view on the experimental set-up employed at Fraunhofer IPT, Aachen, Germany).

Optimum process conditions are needed to ensure good consolidation and adhesion between subsequent layers [62]. The bonding temperature at the location where incoming tape and the substrate come in contact, the so-called nip-point, is widely regarded as the most important parameter among the process variables governing the consolidation quality [6]. In [28], it is clearly stated that unwanted overheating causes negative effects on intralaminar void content, intralaminar bond strength and residual stresses. Several efforts have therefore been made towards analyzing the temperature distributions on the substrate and incoming tape to define the nip-point temperature, e.g. in [63] using fiber-Bragg grating (FBG) sensors and a thermocouple, in [12, 64, 65] using thermocouples and in [66] using an infrared thermographic camera. In [67], carbon fiber reinforced PA12 composites were employed for

the LATP process on flat surfaces. Other thermoplastic materials like PEEK CF, PPS CF and PA6 CF were also utilized for placement on flat surfaces in [68],[19] and [69], respectively. For a continuous ring winding (circular shape) via the LATW process, an experimental and a numerical study were also performed on PEEK CF in [37].

In order to have a reliable and consistent product performance, the bonding temperature at the nip-point should remain at a constant, optimized value for each deposited layers. However, it is very difficult to achieve a constant nip-point temperature due to the following phenomena that inherently take place in LATP/LATW processes:

- variation in material properties [66];
- variation in fiber volume fraction and distribution in the tape and substrate [66];
- variation in porosity, roughness and thickness in the incoming tape [66];
- variation in the geometrical position of the deposited tapes which can result in gaps and overlaps in the substrate [70];
- variation in the roller force due to the variation in the local stiffness of the mold/mandrel or deformation of the roller.

These variations directly influence the absorption and reflection behavior of the tape and substrate which are fiber orientation and incident angle dependent [30]. In addition, the previously deposited layer's temperature in a continuous LATW process has an influence on the nip-point temperature. A variation in the roller force results in a variation in the local deformation in roller and/or substrate which affects the location of the nip-point and local reflections on the tape and substrate. The process parameters have therefore to be controlled in order to compensate for such variations in temperature during the process. In [66], the effects of variation in material properties, thickness and fiber volume fraction on the substrate temperature were studied statistically in an LATW of AS4/PEEK composites. A coefficient of variation of approximately 2.5-5 % was estimated for the temperature variation in the range of approximately 9-20 °C. It was concluded that the uncertainties in the material properties and process dynamics can result in a significant variation in the thermal response with considerable impact on the industrial applications. However, apart from this study, in literature there has been no study on the variation in tape and substrate temperature during continuous LATW of thermoplastic composites by taking the geometrical disturbances into account. The determination of the coefficient of variation (COV) in temperature evolution is utmost important for reliable continuous LATW processes and process optimization.

Understanding the process temperature development and describing the variations in material temperature and process parameters are key in order to develop proper computational

models and in-line process control strategies for LATW of thermoplastic composites [71, 72]. Therefore, the main objective of this paper is to analyze the temperature evolution quantitatively and statistically by a closer look at the variations in the process parameters and setup. The analysis of the temperature development during an adjacent continuous hoop winding process of a type-IV pressure vessel is presented in this paper. A total of five vessels were manufactured in which the temperature distribution in the tape and substrate were measured using an infrared thermal camera. The measurements were performed only for the LATW of the first three layers which were deposited on a thermoplastic liner. A statistical characterization of the measured tape and substrate temperature was made for each layer together with the variation in roller force and tape feeding velocity for the first time in literature. The influence of the geometrical disturbances, such as dimensional irregularities in the liner, on the temperature was determined by using thermographic images and employing a Fourier analysis of temperature, roller force and tape feeding velocity.

3.2 Experimental work

The composite pressure vessels were manufactured with the in-house developed PrePro3D system at Fraunhofer IPT. The type-IV pressure vessels consist of a polymer liner and additional adjacent hoop and helical fiber-reinforced tape layers. This section describes the materials and the method for the manufacturing of thermoplastic composite pressure vessels.

3.2.1 Materials and setup

The pressure vessel was composed of a blow-molded HDPE polymer liner and a number of layers of a unidirectional (UD) tape of glass fibers embedded in an HDPE matrix. The utilized UD-tape was Celstran CFR-TP HDPE GF70-01, which was a 70% E-glass by weight with a fiber volume fraction of 47% [73]. The tape thickness was 0.25 mm and the tape was slit to a width of 25 mm for adjacent hoop winding on the cylindrical part of the liners. The melting temperature of the HDPE ranges between 108-134 °C [74]. The dimensional specifications of the 40-liter tank liners are shown in Figure 3.2. The blow-molded polymer liners provided by HBN-Teknik A/S exhibited a nominal thickness of 5 mm and were equipped with boss pieces out of polymer and metal at the dome parts. The laser absorption of the tank liner is sensitive to the composition of the HDPE, the tank liner thickness, possible heat treatments, the amount and type of pigments added and the surface finishing [6, 75, 74]. The blow molded HDPE liner employed in this research featured a relatively small edge due to the mold parting line as indicated in Figure 3.2. The rough dimensions of the mold parting line

on the cylindrical part were 0.5 mm as width and 0.1 mm as height which may affect the temperature evolution locally. The connection between the tank liner and the rotating pipe was made by six screw elements. The rotating pipe was supported by two bearings with 58 mm distance to the tank liner. There were also two bearings supporting the tank liner in direct contact on the other side of the tank liner (end of cylindrical part of the tank liner).

Fig. 3.2 Schematic of 40-liter tank liner dimension (640.4 mm as length and 272 mm as diameter), the blow-molded edge along tank length and fixation of tank liner with the pipe by screw elements and bearings are shown. The rough dimensions of the blow-molded edge on the cylindrical part are 0.5 mm (width) and 0.1 mm (height).

The processing of the pressure vessel liners was executed with time independent constant input parameters based on processing knowledge of Fraunhofer IPT and initial parameter trials as no data was available in literature for processing of glass/HDPE thermoplastic tape through LATW. Further details regarding the process parameter selection are not mentioned here, since the focus of this paper is solely on the characterization of the variation in temperature during continuous LATW of glass HDPE tanks.

On the basis of the cumulated results of all trials, the deposition velocity of the reinforcing tape was set to a nominal value of 140 mm/s, the laser power was kept constant at 900 W and the compression force exerted by the consolidation roller was set to a nominal value of 105 N as the threshold for ensuring sufficient intimate contact. The force was exerted by the flexible roller developed by Fraunhofer IPT [78] and can be modeled as a spring-damper system.

An LDF 3000-40 VGP diode laser with wavelength of 935-1030 nm $\pm$ 10 nm and the total laser power 3300 W cw by Laserline GmbH was employed as a heating source [76]. The laser power remained constant during the process. A uniformly distributed rectangular laser

Fig. 3.3 Schematic view of the laser source characteristics including laser intensity distribution and profile. The laser optics were attached to the winding head which was ~ 400 mm away from the nip-point. The laser divergence caused a larger laser spot as 32×67 mm at the nip-point [76, 77]. The pink color in the snapshot image represents the laser which is irradiated on the tape, roller and liner at the beginning of the process (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

spot size of 14×28 mm at the aperture was realized by the laser optics which is represented in Figure 3.3. This rectangular spot became larger due to the laser divergence at the nip-point, similar to the configuration represented in [36]. The size of the irradiated area at the nip-point which was approximately 400 mm away from the laser optics had a length of 67 mm and a width of 32 mm on a plane parallel to the laser aperture [77]. The spot size was determined as larger than the tape width to ensure covering the whole material surface by the laser irradiation.

The dimensional configuration of the assembled laser optics is seen in Figure 3.4 (in this picture, ϕ_1 and ϕ_2 are 28 and 32, S_1 and S_2 are 370 mm and 210 mm, respectively).

The measurement of the tape and substrate temperature was carried out with an infrared thermographic camera from DIAS Infrared (type: Pyroview 380Lc) located just above the laser optics enabling image acquisition at frame rates of 50 Hz.

The technical specification of the infrared thermographic camera consists of: aperture angle as 22×16 , spectral range as $8\text{--}14 \mu\text{m}$, measurement temperature range as $0\text{--}500$ C, resolution as 384×288 pixel. The sensor was based on an uncooled microbolometer array with a measurement uncertainty of approximately 2 K when the object temperature is below 100 C and otherwise 2% of the measurement value in C. The more details of thermographic temperature acquisition, the control interface, data transmission and imaging can be found in [79].

Fig. 3.4 Schematic of LATW setup configuration of pressure vessel manufacturing. Moving direction of liner and consolidation roller, tape feed direction, laser optics, thermal imaging camera (TIC), substrate and spring-damper system are shown in this picture. ϕ_1 and ϕ_2 are 28 and 32, S_1 and S_2 are 370 mm and 210 mm, respectively.

Characteristic average values for the tape and substrate temperature were extracted from the acquired images from areas of $5 \times 5 \text{ mm}^2$ located at a distance of 10 mm above and below the nip-point, respectively. The measurement zones were chosen based on experience and best practice from Fraunhofer IPT. The determined measurement areas are shown in the thermographic camera image in Figure 3.5.

A thermographic image during the lay-up process in the first round are also illustrated in Figure 3.5 (b) which indicates the formation of gap/overlap due to geometrical disturbances such as unroundness and eccentricity. Distance "A-B" between the tape edge (to be placed) and the edge of substrate (already wound tape) shown in Figure 5(b) indicates the gap formation during the first round. A positive value of this parameter shows the gap between these two edges, a negative distance shows the overlap on two edges and zero value of "A-B" distance indicates a perfect lay-up regarding geometry [77].

The average temperature values of the measurement areas were extracted and employed for the analysis in this paper.

The emission coefficient of the UD glass/HDPE thermoplastic prepreg tape for extracting temperature is temperature and angle dependent (angle of thermal camera toward the material). The value of emission coefficient employed for the temperature calculation by the camera software (PYROSOFT version 3.17.0.3 from DIAS Infrared GmbH) was set to 0.9 based

on emission coefficient measurements performed with the glass/HDPE fiber-reinforced tape (see possible sources of non-contact measurement error in the Appendix).

The value was set to 0.6 for the pure HDPE liner surface at the first round when the tape was deposited directly on the liner (the value was derived based on the experimental analysis in [80]). Additional sensors were embedded in the tape winding head to transmit actual values of the tape tension, compression force and tape feed velocity which is seen in Figure 3.6. The tape and substrate temperature as well as other measured parameters were recorded throughout the LATW process for tank reinforcement by an in-house developed Beckhoff-based Programmable Logic Controller (PLC). It can monitor the process stability and give the operator the possibility of in-process adjustments, if the values lie outside of predefined and knowledge-based process boundaries. This model also regulates the compression force against possible misalignments in the system, i.e. gaps and overlaps in the deposited tape [70] via a closed-loop control in order to keep enough contact between the consolidation roller and the tank liner [81].

3.2.2 Process kinematics

The HDPE tank liners were reinforced with seven layers (executed through seven rounds) of tape on top of each other according to the requirements set by desired burst pressure and determined layup. The total reinforcement thickness is equal to 1.75 mm. First, three rounds of adjacent hoop layers were applied continuously on the cylindrical part, followed by four rounds of helical layers covering the entire liner including cylindrical and dome parts. The focus of this paper is on the adjacent hoop winding of the tapes on the tank liner. Successful implementation of these layers is important to the quality of the end product and key phenomena observed and understood with this process can also be applied to the case of the more complicated helical winding process that will be studied at a later stage. The kinematic of the adjacent hoop winding process is outlined as a lateral movement of the tape winding head from the beginning to the end of the cylindrical part while the tank liner is rotating at a constant angular speed. During this movement, a possible eccentricity might occur due to the fixation setup, and deformation of the tank liner (see subsection 3.2.1 "Materials and setup"). The eccentricity generates a distance between the tank liner axis and the rotation axis which may result in a variation in the tape feeding velocity and roller force. The system technology accounts for this possible eccentricity by a spring suspension of the compression roller, which is able to maintain a constant pressure value in the nip-point. However, this adjusting movement leads to deviations in the nip-point location observed by the stationary thermographic infrared camera and irradiated by the stationary laser optics.

Fig. 3.5 (a) Thermographic image from DIAS Infrared (type: Pyroview 380Lc) for extracting tape and substrate temperatures from indicated areas (boxes) during the LATW process. In this image, isothermal regions are shown with their boundaries on the tape and substrate. (b) The distance "A-B" is realized between the tape edge (to be placed) and the edge of substrate (already wound) at the nip-point in the first round (winding on polymer liner surface). This distance indicates creation of gap or overlap in the first round (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

The winding angle was determined as $\pm 88.2^\circ$ which allows the continuous adjacent winding of the tapes (25 mm width) on a liner with 272 mm diameter. The end position of one round constitutes the start position for the next round as the adjacent hoop winding was executed continuously. After the first round, the moving direction is reversed and the head is laterally moving back to the beginning of the cylindrical part of the liner (round 2).

This transition from one round to the next round also includes changing winding direction which is amounted as 3.6° (changing winding angle from $+88.2^\circ$ to -88.2° or vice versa).

Fig. 3.6 Sensors locations for measuring tape tension, tape feeding velocity and roller force. The locations of the tape and tape feeding spool are also shown.

This procedure continues for three rounds as shown schematically in Figure 3.7. In each round, the liner rotates 22 times resulting in a placement of 22 adjacent annular cycles of the tape. Each round of adjacent hoop winding takes roughly 134 seconds based on the average tape feed velocity, liner diameter, winding angle, and length of the cylindrical part of the liner (~ 640.4 mm). Thus winding three rounds on a tank takes roughly 6 minutes and 43 seconds (~ 403 seconds). The described procedure in this section for manufacturing type-IV pressure vessel was executed for five tanks in a similar way in order to have reliable and repeatable results.

Fig. 3.7 Schematic view of continuous winding kinematics for three rounds of adjacent hoop winding on the cylindrical part of the HDPE tank liner. The winding angle was ± 88.2 degree.

3.3 Results and discussion

An interim and a final result of pressure vessel manufacturing through the LATW process are shown in Figure 3.8. One of the products is visible after three rounds of adjacent hoop winding and a final product followed by four rounds of helical winding covering the entire tank liner. This chapter focuses on the explanation of the observed phenomena during the first three rounds of adjacent hoop winding (see Figure Figure 3.8(a)). It also provides an assessment of process stability and repeatability.

Fig. 3.8 (a) Tank liner at the end of three rounds of adjacent hoop winding and (b) the final product of pressure vessel including three rounds of adjacent hoop layers followed by four rounds of helical layers covering the entire body (see Section 2 for description).

3.3.1 Temperature evolution and variation

Five tanks were continuously wound with identical conditions. In all cases the laser power was held constant during each round. The temperatures of the tape and the substrates were measured in a continuous fashion from the beginning to the end of the tape winding process, see Figure 3.9.

In this figure, the temperature data of all tanks are shown for the tape and substrate.

The following trends are visible for the temperature developments of all tanks:

- Round 1: The substrate and tape temperatures showed an approximately constant baseline with a large number of spikes on top for the substrate. Over the whole range of the first round the substrate temperature was about 10 °C lower than the tape temperature. The substrate and tape temperatures showed some degree of variation in temperature (± 5 °C) about the baseline along with the already mentioned positive spikes with magnitudes from 40 °C up to 80°C.
- Round 2: The substrate temperature suddenly increased to temperatures about 75 °C higher than at the end of round 1, whereas the tape temperature only showed a

minor increase of about 10 °C. The substrate temperature in this round was always larger than the tape temperature. The substrate temperature showed a decreasing trend with the temperature dropping from 190 °C to 170 °C whereas the tape temperature decreased only a few degrees Celsius. The substrate temperature was showing much more variation in temperature than the tape temperature. The variation in the substrate temperature was comparable to that in round 1. In round 2 strong local variations in temperature occurred as well for all tanks, but both in the positive and negative direction.

- Round 3: The tape temperature is changed hardly as compared to the previous round. The substrate temperature showed a strong increase at the start of round 3 of about 40 °C, but it leveled off to an approximately constant value with a significant amount of variation. Also in round 3 strong local variations in temperature occurred.

In order to quantify process variations, histograms of the measured process parameters were analyzed. The histograms of the temperature variation in the first, second and third round for each tank are illustrated in Figure 3.10 and Figure 3.11 for the substrate and tape, respectively. The corresponding mean and standard deviation of the temperature distributions in each round are given in Figure 3.12 for the substrate and in Figure 3.13 for the tape. Here, the standard deviation was estimated with and without subtracting the moving average of the temperature evolution from the actual measurement. An example of the substrate temperature with and without subtracting the moving average temperature is depicted in Figure 3.14 for Tank-2. It is seen from Figure 3.12 that the mean substrate temperature increased gradually and was approximately 125 °C, 175 °C and 195 °C for the first, second and third round, respectively. The standard deviation of the substrate temperature was approximately 8 °C, 12 °C and 6 °C for the first, second and third round, respectively without subtracting the moving average. These values slightly decreased when the moving averages of the temperatures were subtracted. The increase in standard deviation from the first to second round and the decrease in standard deviation from the second to third round were consistent for the substrate and are discussed further in the following sections. A similar trend was observed for the mean tape temperature which was approximately 130 °C, 142 °C and 145 °C the first, second and third round, respectively. The standard deviation of the tape temperature was in general smaller than the standard deviation of the substrate temperature with subtracting the moving average temperature. The coefficients of variation (COV) of the tape and substrate temperatures are depicted in Table 3.1. It is seen that the COV was 4.8-8.8 % for the substrate temperature and 2.1-7.8 % for the tape temperature. In the following the observed trends based on the temperature evolution are discussed in more detail.

Fig. 3.9 Tape (a) and substrate (b) temperature of three rounds adjacent hoop winding of five manufactured tanks via the LATW process. Each rotation takes roughly 6.2 s.

Fig. 3.10 Histogram of the substrate temperature in the first, second and third round for all pressure tanks (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

First round

At the start of the first round the deposition head was placed closely to the tank liner and the tape is brought into contact with the liner. The liner was accelerated up to a nominal rotational velocity of about 140 mm/s. The laser was switched on as well and immediately started to heat up the tape and substrate. As long as the liner had not reached the nominal velocity, a slight overheating of the liner occurred which is visible as the first peak in tape and substrate temperatures at the start, see Tanks 1 and 5 in Figure 3.9. After the start of the process the deposition head moved with a constant velocity parallel to the axis of the liner from the start position to the end of the liner. For Tank-2 the laser power was accidentally too low during a short period of time after the start explaining the relatively low temperatures. Similar phenomena related to a small degree of in-synchrony can also be observed at the end of round 3 when the tape winding process was stopped for some of the tanks.

Throughout the first round, the tape and substrate temperature remained more or less constant with distinctive peaks visible in the substrate temperature. Every time the laser irradiated the blow-molded edge part of the liner, which was formed during the blow-molding process of the tank liner (see also Figure 3.2), a temperature spike appeared. The number of spikes was identical to the number of rotations the tank made when covering the liner

Fig. 3.11 Histogram of the tape temperature in the first, second and third round for all the pressure tanks (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Fig. 3.12 Substrate temperature: The mean (μ) (a), corresponding standard deviation (σ) without subtracting the moving average temperature (b) and standard deviation with subtracting the moving average temperature (c) for the first, second and third round.

Fig. 3.13 Tape temperature: The mean (μ) (a), corresponding standard deviation (σ) without subtracting the moving average temperature (b) and standard deviation with subtracting the moving average temperature (c) for the first, second and third round.

Fig. 3.14 The substrate temperature evolution for Tank-2 with and without subtracting the moving average. Length of moving average interval is considered as 1 s.

with a layer of tape during the first round as seen in Figure 3.9. The magnitudes of the peaks depended on the geometry of the blow molded edge such as the shape and height [74] and therefore vary from tank to tank. The edge caused local energy concentration and hence sudden temperature elevations in the substrate temperature that may deteriorate the liner due to thermal and chemical degradation. Such excessive temperature values should be avoided in general.

Table 3.1 The coefficient of variation ($COV = \mu/\sigma$) of the temperature variation in substrate and tape without subtracting the moving average temperature for tank liners represented as T-1 to T-5 (see Figure 3.9).

	COV [%] substrate			COV [%] tape		
	First round	Second round	Third round	First round	Second round	Third round
T-1	5.8	6.9	2.9	2.2	2.1	2.1
T-2	7.9	8.0	3.6	2.9	7.2	7.8
T-3	4.8	6.3	3.4	2.0	3.2	5.9
T-4	5.1	7.4	4.2	2.8	2.6	2.9
T-5	8.8	7.6	3.4	3.3	4.6	4.4

During the first round some variation in tape and substrate temperature was visible, apart from the observed spikes, that may be ascribed to variations in laser absorption of the liner and the tape as well as variation in material properties. Surface asperities and texture along with complex absorption mechanisms of the pure polymer pigmented HDPE tank and the glass fiber-reinforced HDPE tape can explain this behavior [74, 82, 6].

Second round

The second round started immediately after the first round with the tape winding head moving parallel to the liner axis in opposite direction from the end to the start position while the liner continued to rotate with the same velocity (140 mm/s). At the beginning of the second round, sharp increases in the substrate temperatures were observed with high peak temperatures considerably above those at the end of the first round. There are two reasons explaining this observation. Firstly, the deposition process was continued in reverse direction while the substrate was still relatively hot from the deposition of the first layer. The laser power remained unchanged causing a significant increase in the substrate temperature. Secondly, the substrate material changed from a pure HDPE (liner) in the first round to a glass/HDPE composite, i.e. the deposited tape, in the second round affecting the amount of energy absorbed from the supplied laser irradiation.

During the deposition of the tape in round 2 the average substrate temperature showed a continuous decrease to approximately 160 °C at the end of the round 2 for all tanks. The temperature decrease was mainly caused by cooling of the substrate. After a point on the tank liner surface was covered by tape during round 1, it started to cool down from the process temperature of approximately 130 °C. It depended on the amount of time for the tape winding head to move further to the end position and move back towards the start position how far

the temperature may drop. The closer a point at the substrate was to the start position, the longer the time allowed for cooling and the further the temperature dropped in line with the observed substrate temperature development in round 2.

The apparently random peaks in the substrate temperature profile in the second round had a magnitude of smaller than 30 °C. The reason of these peaks may be found in anisotropic reflections at the surface of the substrate due to non-ideal stacking of layers on top of each other causing local gaps in between tapes or overlap of adjacent tapes from the first round (see [70] for gap/overlap and [39, 83] for effect of laser reflection). This resulted in an increase in the COV and standard deviation in the second round as compared with the first round (see Figure 3.12 and Table 3.1). The origin of these local gaps and overlaps and other potential sources like fibers are discussed in the next section.

The tape temperature remained more or less constant with some scatter in between approximately 130°C to 145°C with a COV of 2.1-7.2 %. Its mean value slightly increased with respect to the first round as seen from Figure 3.13 due to a larger scattering contribution from the substrate, which obtained a higher temperature during round 2 as compared to round 1. Another reason of increasing tape temperature at the beginning of this round especially for Tank-2 or Tank-5 is changing measurement location. This will be discussed in detail in the next section.

At the end of the second round, a sudden drop of the substrate temperature can be observed with a magnitude up to about 60 °C. Here, the tape winding head moved beyond the starting point to a relatively cool part of the tank liner in the turning point between the second and the third round where no previously wound tape is present (uncovered part).

Third round

In the third round the tape winding head moved again parallel to the liner axis from the start to the end position similar to the first round. The substrate temperature showed a strong peak at the beginning of the round for the same reason as it did at the start of the second round. The third layer was deposited on top of the second layer immediately after the second layer was deposited, so the substrate was still relatively hot while the laser power remained unchanged. Here, the temperature peaked at about 210 °C and during the third round it decreased to a fairly constant value of about 185 °C. This value was mostly above the substrate temperature of the second round indicating a further heating of the substrate during the third round. Apparently, heat loss to the environment was not sufficient to keep the substrate from heating up which is also due to heating of the air enclosed within the tank liner.

On close inspection during the transition from the second round to the third round, a physically unrealistic drop in the substrate temperature was observed for all tanks with a

magnitude of almost 100 °C at $t = 270$ s just before the temperature strongly increased. This drop was partly related to the tape being deposited on a relatively cold uncovered section of the tank liner, where no tape had been deposited before. The main reason, however, was that starting from the second round onwards the emission coefficient of the tape was being used to interpret the thermal camera data of the substrate and illuminating uncovered liner material obviously led to wrong temperature data as the emission coefficient of the liner (0.6) differs from that of the tape (0.9), see also subsection 3.2.1 "Materials and setup". Although the tape temperature remained more or less constant with some scatter in round 3, the profiles of Tanks 2 and 3 showed a relatively steady increase of the tape temperature up to $\sim 50^\circ\text{C}$. As explained before, this behavior is related to the changing measurement location which will be elaborated in next section.

The COV and standard deviation of the substrate temperature decreased in the third round as compared with the second round as can be seen from Table 3.1 and Figure 3.12. This reduction in standard deviation can be due to the influence from the liner surface. The gap in between the deposited tapes was not as dominant in the third round as in the second round, i.e. the possible gaps between the deposited tapes in the third round consisted of the tape material instead of the pure HDPE liner as in the second round.

At the end of the third round, a drop of temperature for both tape and substrate can be observed as the laser source is shut down. For some tanks prior to this temperature drop, a sharp rise in the tape and substrate temperature appeared, see for example Tank-1. This phenomenon was related to a small in-synchrony between shutting down the laser source and stopping the roller and tape movement.

3.3.2 Geometrical disturbances

The highly localized substrate temperature spikes in the first round claimed due to the blow-molded edge were explored via the thermographic measurements. The exemplary thermographic snapshots in the first round showing polymer material inhomogeneity and blow-molded effects as well as defect-free surface of polymer liner are displayed in Figure 3.15. The increase of substrate temperature due to the blow-molded edge effects are in accordance with explanations in subsection 3.3.1 "Temperature evolution and variation". The temperature spike, i.e. the temperature increase, in Figure 3.15 (c) due to blow molded edge was found to be approximately 43C as compared with the image shown in Figure 15 (b). In order to quantify the temperature variation due to the aforementioned effects, a path was drawn in Figure 3.15 as illustrated a line from point P1 to point P2. The temperature variation along the path P1-P2 is plotted in Figure 3.16. It is seen that the temperature was approximately 120C for the defect-free case with a slight variation. The material in-

homogeneities of the polymer liner caused an increase in the mean temperature which was approximately 135 C and its variation was found to be approximately 10 C. The change in surface topology and roughness might have caused this increase and variation in the substrate temperature. The blow-molded edge had the most influencing effect where the mean substrate temperature reached approximately 165 C with a maximum value of approximately 170 C. The blow-molded edge can be considered as locally a rough area where the laser irradiation was localized and hence resulted in a sharp increase in the temperature.

Another possible geometrical disturbance was the eccentricity which caused a non-uniform liner movement and hence affected the location at which the thermal camera measurements were recorded. This is illustrated for Tank-2 in Figure 3.17 in which three different locations for the measurement box for substrate, tape and nip point are shown. It should be noted that the movement of the measurement box is present only when there is an eccentricity. As a consequence, the change in tape temperature due to the movement of the measurement box was obtained approximately as 44C according to the frames shown in Figure 3.17 which was aligned with the increase in tape temperature for Tank-2 as seen in Figure 3.9.

The gap and overlap formations were captured using the thermographic images which are displayed in Figure 3.18. The origin of these regions with gaps/overlaps lied in the non-ideal shape of the liner (being slightly unround during tank liner production or deformation due to exerted roller force) and the unwanted eccentric fixation of the liner on the tape winding device. These local features caused a variation in the temperature measured by the thermal camera mainly due to the change in the local geometry which affected the heat absorption and laser light reflection locally. In addition, the emission coefficient used in the thermal camera needed to be updated with respect to the local geometry which was not the case during the experiments. To illustrate, in the case of gap during the second round, the HDPE liner material was visible for the camera, which caused a lower temperature recorded by the camera. On the other hand, in the case of an overlap, the laser irradiation was localized providing a sharp increase in substrate temperature. At this situation, the emission coefficient needed to be lowered at this time frame due to high temperature (see Appendix for the variation in emission coefficient with respect to the temperature). The path P1-P2 defined in Figure 3.18 was used to quantify the temperature variation at the gap/overlap regions. The temperature variation profile along P1-P2 path (extracted from pixels) is shown in Figure 3.19. The locations of the gap/overlap in the temperature profiles were related to the pixels containing the gap/overlap in the thermographic images. The emission coefficient (EC) of the pixels (pixels 37-39) with gap was adapted manually with correct value from the polymer liner in order to show the influence of this effect. The temperature dropped from approximately 210 C to 135 C due to the gap. By adapting emission coefficient to

0.6 (was 0.9) for the pixels constituting the gap, the corrected temperature was estimated approximately as 170 C due to the gap as seen in Figure 3.19. On the other hand, the substrate temperature increased to approximately 235 C due to the overlap.

In order to evaluate the temperature variation excluding the gap/overlap on the substrate, e.g. during the second round, a total of 50 images which did not include the gap/overlap were selected randomly at different time stamps. The temperature variation along P1-P2 path was analyzed for each thermal image and plotted in Figure 3.20. Total of 25 pixels were considered on P1-P2 path. The mean average of the temperature along P1-P2 path was subtracted from the temperature profile along the path P1-P2 in order to quantify the measured temperature variation due to a possible material homogeneity. The temperature values for each pixel along the path P1-P2 were grouped for the 50 images and represented as a box and whisker plot in Figure 3.20. This chart shows distribution of data into quartiles, highlighting the mean, median and outliers. The boxes, which represents 50% of the data set, have the lines extending vertically called "whiskers". These lines indicate variability outside the upper and lower quartiles of the observations, and any point outside those lines or whiskers is considered as an outlier. The mean is marked as central cross and median is shown by a horizontal line inside the box as shown in Figure 3.20. Approximately 5C variation (length of boxes) was observed as a general trend for each pixel. The most of the outliers were observed approximately as 10C and few of them were found to be approximately 25C. The outliers with high scatter might be due to a possible nonuniformity of the fiber distribution or the change in orientation of the material surface (see Appendix for the variation of emission coefficient with respect to the thermal camera angle).

The periodical vertical change in the nip-point position can be determined by analyzing the roller force distribution for each round which can be seen in Figure 3.21. It is seen that much random scatter was the case for all the rounds as compared with the tape and substrate temperature distributions seen in Figure 3.10 and Figure 3.11. Although the nominal roller force was set to 105 N, roller force clusters were observed relatively lower and higher force values, e.g. 97 N and 117 N for Tank-2; 102 N and 118 N for Tank-3; 106 N and 115 N for Tank-5. These clustering of the roller force clearly indicates a periodicity in the liner response with respect to the exerted roller force. To illustrate, the development of the roller force during the tape winding process of Tank-2 is displayed in Figure 3.22. During most of the first round the mean and standard deviation of the roller force were more or less constant for Tank-2, however towards the end of round 1 the mean value increased and the standard deviation decreased. In round 2 the mean value reduced to a more or less constant value similar to that in the first part of round 1 and this value was also maintained in the first half

Fig. 3.15 Thermographic images of the irradiated area near the nip-point in the first round. (a) No edge/ material inhomogeneity (defect-free surface), (b) effects of material inhomogeneity and (c) blow-molded edge of the polymer liner (substrate in first round) are displayed. The path P1-P2 is drawn in the width direction of the substrate to get quantitatively variation of the temperature due to the mentioned effects (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Fig. 3.16 Temperature variation of path P1-P2 in the first round due to the material inhomogeneity and blow-molded edge of the polymer liner as well as defect-free surface which are represented graphically in Figure 3.15.

Fig. 3.17 Thermographic images of the irradiated area near nip-point in the second round indicating the movement of the thermal camera measurement targets at tape, nip point and substrate. (a) Correct measurement location, (b) upward and (c) downward movement of the measurement locations due to the unavoidable eccentricity (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

of round 3. In the second half of round 3 an increase in the mean roller force was observed with a concomitant reduction of the standard deviation. The locations of these changes at the end of the first and third round are related to a relatively large stiffness at the dome part of the tank (the right side of tank liner in Figure 3.7) where the cylindrical part of the tank liner is supported by two bearings. Fluctuations in the roller force were caused by changes in the vertical position of the consolidation roller, as can be learned from Figure 3.4, where the spring/damper construction attached to the consolidation roller is displayed. The roller force oscillations in Tank-2 were analyzed through a Fourier analysis of the force-time signal in Figure 3.23. Here, the relative magnitudes of the signals as a function of the frequency are displayed for the three rounds, where the data at some distance from the start and end positions was selected (in order to eliminate the effect of transition parts between rounds). In line with the repetitive nature of the roller force oscillations, distinctive peaks in frequencies can be observed that can be related to the tape winding process. The first peak at a frequency of about 0.16 Hz corresponds to a periodic signal with a period of 6.2 s, which exactly corresponds with the time it takes for the tank liner to make a revolution. The other peaks may be regarded as higher orders or can be related to other periodic signals. For example, the signal at 0.43 Hz can be related to the time it takes for the consolidation roller to make a revolution. On closer inspection indeed the roller showed some geometrical inconsistencies that could very well explain the presence of this signal. Hence, the observed variations in the roller force can directly be related to the rotational nature of the tape winding process. The local variations in liner diameter related to unroundness and excentricity can lead to the formation of small gaps and regions with some tape overlap due to the trajectory change. In turn the regions with gaps/overlap may cause irregular reflection/absorption behavior of the

Fig. 3.18 Thermographic images of the exemplary (a) gap and (b) overlap in the second round which cause localization of the substrate temperature. The path P1-P2 is drawn in the width direction of the substrate to get quantitatively the maximum (shown in the pictures) and variation of the temperature due to the gap/overlap effects (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Fig. 3.19 Temperature variation of path P1-P2 in the second round due to the gap and overlap of wound tape (substrate) which are represented graphically in Figure 3.18. Manually adapted emission coefficient (EC) of the gap region is also added.

laser rays leading to different substrate temperature values, both above and below typically expected values. This largely explains the substrate temperature variation in the second and third round (see Figures 9, 10 and 12).

In addition to the roller force, the tape feeding velocity was also affected by the geometrical disturbances, i.e. the unroundness and eccentricity. The histogram of the tape feeding velocity for each round is shown in Figure 3.24. It is seen that the velocity distribution trend was almost the same for each round and the distribution was very close to the normal distribution where the nominal set value was 140 mm/s. The mean and standard deviation of the measured velocity were approximately 143 mm/s and 5 mm/s, respectively. To illustrate, the measured velocity data, moving average values and moving standard deviation of adjacent hoop-winding for Tank-2 are shown in Figure 3.25. The variation of measured linear velocity is roughly 10 mm/s with some spikes that amounts to 20 mm/s.

A Fourier analysis of the tape feeding velocity, temperature of tape and substrate data was conducted in a same manner as the roller force analysis which is shown in Figure 3.26 for Tank-2. The same dominant frequencies observed from the analysis of the roller forces are observed for the tape and substrate temperature deviations providing strong evidence that the variations in the roller force and both temperatures were linked. The unroundness and eccentricity also caused variations in the required supply speed of the tape that was deposited on top of the tank liner and the tape tension. The actual supply speed is equal to the tangential velocity at the nip-point which in turn is dependent on the local value of the tank liner

Fig. 3.20 Box and whisker plot representing temperature variation at indicated pixels (path P1-P2 in the width direction of the substrate) for randomly selected 50 frames images. Note that the images containing edge effect/gap/overlap are excluded in the selection procedure and the mean average of the temperature along P1-P2 path was subtracted.

diameter. Unroundness and eccentricity cause temporal variations in the diameter and, in turn, in the required supply speed. As the laser source supplies a constant power, the heating rates of the tape may temporarily change, depending on the tape speed. The larger the local tape speed, the smaller the temperature increase of the tape at constant laser power. This also holds to some extent for the substrate surface heated by the laser source. A Fourier analysis of the tape speed, carried out in the same way, indeed shows that the frequencies present in the tape temperature, substrate temperature, tape tension and roller forces can explain the speed variations observed, see Figure 3.26 for the results of the analysis of Tank-2.

3.3.3 Process improvement

The laser assisted adjacent hoop winding of three rounds on a tank liner at constant laser power can be done well but led to significant changes in the process temperature during the deposition process. The optimal and well-controllable conditions should be achieved during the tape winding process for the superior manufactured product. As observed from the results presented in this work, such ideal manufacturing conditions due to the geometrical disturbances cannot be established. Therefore, suitable approaches should be developed to control the temperature evolution globally and locally as well as fluctuations in temperature due to geometrical disturbances. This is necessary to optimize the final part properties with a better understanding of the thermal history of the material.

Although the feedback temperature controller seems to be a solution to ascertain a constant nip-point temperature, it is not sufficient for process control when the disturbances like measurement location movement or gap/overlap exist. Therefore, there is a need to detect the geometrical disturbances and adapt the thermal camera measurements accordingly, e.g. the measurement location and emission coefficient of the thermal camera. A potential solution for this is the real-time object detection technique using the deep-learning methods such as RCNN, YOLO or SSD [84–86]. This can be integrated into the LATW system. The real-time object detection can also be used for realizing gap and overlap where the emission coefficient is changing. At these locations, thermal camera should use different emission coefficient to measure the right temperature. Adapting laser power for the desired temperature at those regions needs such a laser like VCSEL laser (see [67]) which could precisely adjust its power toward the gap/overlap regions. Integrating physics-based in-line monitoring model is also another possibility to create such model predictive control model i.e. those developed in [87], in order to interpret the actual temperature and control it for the LATW application.

Fig. 3.21 Histogram of the roller force in the first, second and third round for all the pressure tanks (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Fig. 3.22 Measured roller force data (total number of measured data is $\sim 400K$) and moving average value and corresponding standard deviation (STD) of Tank-2 for round 1, 2, 3. Interval of 5 s for moving mean values was chosen in order to show clearly overall trend.

Fig. 3.23 Discretized pure variation vs time (top figure) of Tank-2 obtained by subtracting the moving average values ($\langle F_{rol} \rangle$) from the original ones (F_{rol}) in round 1, 2, 3. The Fourier analysis (blue lines in bottom figure) of roller force ($\text{fft}(F_{rol} - \langle F_{rol} \rangle)$) along with dominant frequencies at $f_1 = 0.167$ Hz (black dashed lines) and $f_2 = 0.434$ Hz (green dashed lines) for each round are calculated. Other vertical lines indicating factors of f_1 and f_2 are also shown as vertical black dashed line and green dashed line, respectively.

3.4 Conclusion

In this work laser assisted tape winding was used to manufacture a number of type-IV thermoplastic composite pressure vessels. A constant laser power was employed during continuous adjacent deposition of three layers of a glass-filled HDPE thermoplastic fiber tape on an HDPE liner. The development of the substrate and tape temperatures along with other key characteristics of the deposition process were analyzed in detail for a reliable manufacturing. In addition, the variation in tape and substrate temperature was quantified. The following conclusions can be drawn.

Applying a constant laser power while depositing layers of tape on top of each other in a continuous adjacent fashion leads to a non-constant process temperature. The process temperature is sensitive to the average substrate temperature that in turn is dependent on the local heating and cooling cycles induced by the LATW process. Continuing the tape winding process directly after the deposition of the first layer causes a significant increase in the average substrate temperature. The mean tape and substrate temperatures were found to increase approximately by 12 °C and 50 °C, respectively, from the first round to the second round. The temperature change can be attributed both to the change in substrate material (from a bare liner to a first layer of tape on a liner) as well as to the heat accumulated in

Fig. 3.24 Histogram of the tape feeding velocity in the first, second and third round for all the pressure tanks (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

the first round. Heat accumulation also led to an increase of the average tape and substrate temperature of around 3°C and 20 °C, respectively, from the second round to the third round.

The mean temperature of the substrate and tape temperatures increased gradually round by round. However, the trend of the COV and standard deviation was found to be non-linear due to the process disturbances. A larger COV of the substrate temperature (4.8-8.8 %) than the COV of tape temperature (2.1-7.8 %) was found from the histograms of measured temperatures. The standard deviation of the substrate temperature in the third round was found to be smaller than the second round.

The detailed analysis conducted in this paper showed the importance of the relation between process parameters and geometrical anomalies (surface features, eccentricity, un-roundness) that have a severe impact on the actual and/or measured temperature in the process zone. Even the presence of a small blow molded edge may cause a significant increase in

Fig. 3.25 Oscillation in measured tape feed velocity of thermoplastic pressure vessel Tank-2 via LATW process. The total number of measured data is $\sim 400K$. The moving average and standard deviation (STD) of the measured velocity are also depicted. Interval of 5 s for moving mean values was chosen in order to show clearly the overall trend (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

the temperature as observed during the tape winding in the first round via the thermographic images.

This blow molded edge effected periodic scatters in the first round of adjacent hoop winding with an amount of 20-50 °C.

Eccentricity and unroundness of the tank liner caused variations in tape velocity, substrate and tape temperatures which generated reaction forces by the roller as shown through detailed Fourier analysis.

Moreover, the unroundness and eccentricity were found to be the potential reason for the change in measurement location and the occurrence of gap/overlap. The locations on the tank surface with gaps between the deposited tape and overlap of adjacent layers led to considerable local temperature variations during the second and third round. The overall temperature variation was found to be approximately $\pm 5^{\circ}\text{C}$ for the randomly selected 50 thermal images for the substrate in which the gap and overlap features were excluded.

The quantified temperature variations might not be critical to generate unwanted degradation. Nevertheless, they may affect the local temperature history of the material, e.g. the cooling rate and the temperature at consolidation may differ, which drives the mechanical property evolution via crystallinity, residual stresses, etc. It is therefore vital to understand,

Fig. 3.26 Fourier analysis (blue color) of: (a) velocity, (b) tape temperature and (c) substrate temperature of Tank-2 along with dominant frequencies at $f_1=0.167$ Hz (black dashed lines) and $f_2=0.434$ Hz (green dashed lines) in round 1, 2, 3 are calculated. Other vertical lines indicating factors of f_1 and f_2 are also shown as vertical black dashed line and green dashed line, respectively. Note that the Fourier analysis was applied to the values where the moving average was subtracted from the original values, i.e. for the tape velocity $fft(Vtape-<Vtape>)$, for the tape temperature $fft(Ttape-<Ttape>)$ and for the substrate temperature $fft(Tsub-<Tsub>)$.

describe and quantify the variation in temperature during process which would pave the road towards developing more robust inline control strategies. In addition, a well described inherent temperature variation could help the composite structure designers to make more

reliable product designs by taking the possible variations in the thermal history, e.g. the quantified COV data per round, and using it in a stochastic analysis.

Monitoring disturbances with thermographic images and Fourier analysis, it was concluded that a real time adaptive detection of the nip-point location needs to be employed together with a feedback temperature control system in order to take the temperature variations due to geometrical disturbances into account.

3.5 Appendix

An experiment was designed and performed for measuring temperature-dependent emission coefficient of the employed UD glass/HDPE thermoplastic tape which is shown in Figure 3.27. The experiment used the contact measurement thermocouple and the non-contact measurements of UD prepreg which is heated by a heating plate. The experiment was performed for three inclination angles of the thermal camera toward the material which indicates possible measurement error of the non-contact thermographic measurement. The measurements were repeated five times in order check reproducibility and validation of the experiment. Emission coefficients in the camera software set so that the indicated temperature matches the one determined by the contact measurement. Results in Figure 3.28 show the temperature-dependent emission coefficient of the employed UD thermoplastic tape for different inclination angles. The general trend is reported as:

- Emission coefficient values were in the domain of 0.7-1.0
- Emission coefficient of 1.0 was found for low temperatures
- The higher the temperature the lower the emission coefficient
- The lower the inclination angle the lower the emission coefficient
- The behavior change was attributed to the changing aggregate phase of the HDPE material after passing the melting point of the matrix material

Setup for 60° and 90° inclination angle

Fig. 3.27 Experimental setup for measuring temperature dependent emission coefficient of the employed UD glass/HDPE thermoplastic tape for three inclination angle of the thermal camera toward the material.

Fig. 3.28 Temperature dependent emission coefficient results of the employed UD glass/HDPE thermoplastic tape for different inclination angles of the thermal camera toward the material.

Chapter 4

Coupled local and global optical-thermal model for continuous LATW

¹ A numerical process simulation framework is introduced in this paper to describe and predict the process temperature evolution during the laser-assisted tape winding (LATW) process of a type-IV pressure vessel made of glass-reinforced high-density polyethylene (G/HDPE). A local optical-thermal model is fully coupled with a global thermal model for the simulation of continuous adjacent hoop winding cases. The predicted tape and substrate temperatures are compared with the experimental data to validate the process model's effectiveness. The inline temperature was measured by an infrared thermographic camera during the continuous winding. The continuous process temperature of the substrate is affected significantly due to the previously wound layers including the pressure vessel, and a gradual increase of the temperature of the roller and the air inside the liner. A considerable temperature increase calculated as 80-120 °C takes place for the substrate during winding of two consecutive layers of (G/HDPE) prepreg tape at the liner ends. The influence of pressure vessel size on the tape and substrate temperatures is investigated for different liner radii using the validated process model. The peak substrate temperature is found to increase approximately 45°C by reducing the radius of the pressure vessel from 272 mm to 68 mm while maintaining all other process conditions constant.

¹This chapter was part of "A.Z., M.S., I.B., T.C.B., H.J. and R.A., A fully coupled local and global optical-thermal model for continuous adjacent laser-assisted tape winding process of type-IV pressure vessels, Journal of composite materials, 2020 July, DOI.org/10.1177/0021998320944598". A.Z. developed and performed numerical simulation methods and wrote main structure of the paper, M.S. performed experiments, I.B. and T.C.B. provided critical review, H.J. contributed to the methodology and R.A. contributed to the methodology and supervision of research.

4.1 Introduction

Laser assisted tape winding (LATW) is an automated and efficient method to manufacture pressure vessels out of fiber reinforced thermoplastic composites (FRTPCs) for the storage of hydrogen [50] or compressed natural gas (CNG) [88]. The in-situ consolidation of the FRTPCs during the LATW process provides a considerable time saving without an additional consolidation step [60, 67]. Similar to laser-assisted tape placement (LATP) processes, the application of a laser as heat source implies some possible advantages including higher accuracy, repeatability, quality and reduced cycle time compared to conventional methods using hot air, gas or flame [25, 58, 59]. The incoming fiber reinforced thermoplastic prepreg tape is bonded to a liner or an already placed substrate by means of a laser heating and compaction roller during the LATW processes [89]. A schematic view of a LATW process and a picture from a hoop winding process as an example are shown in Figure 5.1. The incoming prepreg tape and substrate come into contact at the so-called nip point. A proper consolidation of the tape and substrate at the nip point requires optimum process settings to keep the consolidation pressure, time and temperature at the nip point at desired levels which is a challenging task in the LATW processes. The inherent variations in geometry and material properties makes the process difficult to control often leading to deviations of the desired temperature at the nip point [66, 70, 90, 91]. In addition, non-constant process temperatures are present during continuous LATW of tape layers on top of each other which was studied extensively in [26] for manufacturing of type-IV pressure vessels made of continuous glass fiber reinforced high density polyethylene (G/HDPE). It was shown that the local heating and cooling cycles during the LATW process significantly affected the process temperature. The characteristics of the tape and substrate temperature developments near the nip point for the continuous LATW process reported in [26] are summarized in Figure 4.2. The previously deposited layers' temperature as well as the heat accumulation during the transition from one round to another round in a continuous LATW process had an influence on the tape and substrate nip point temperatures.

In order to tackle the challenges mentioned above and control the processing temperature in continuous LATW processes, computational process models are needed next to experimental observations to describe and predict the physical phenomena taking place during the manufacturing process. Several studies were conducted in literature to understand the relation between the heat input and the resulting temperature distribution in the tape, the liner/substrate and the compaction roller for thermoplastic automated tape placement (TP-ATP) processes [11–14, 16, 15, 92, 17]. In those works a uniform heat flux was considered as a boundary condition in the thermal model for the tape and substrate temperature predictions. An analytical thermal model was used in [11] for the laser assisted tape placement (LATP)

Fig. 4.1 Description of: (a) the principle and (b) the system technology of the LATW process of adjacent hoop winding (detailed view on the experimental set-up employed at Fraunhofer IPT, Aachen, Germany). The main elements of the LATW process are the laser optics, substrate, tape, roller and liner/mandrel.

Fig. 4.2 The trend of the substrate (*left*) and tape (*right*) temperature developments during continuous LATW process of type IV pressure vessels with three rounds of adjacent hoop layers. Round-1: placing tape on a pure thermoplastic liner. Round-2 and 3: placing tape on the already wound layers. The peaks in substrate temperature are due to the heat accumulation during winding on a previously deposited round. The gradual heating is due to an increase in roller and inner air temperature [26].

process to correlate the tape placement speed with the through-thickness temperature distribution in the substrate. The roller temperature was reported to have the most significant impact on the nip point temperature and incoming tape temperature distribution in [12]. Thermal models were coupled with crystallization models for the LATP in [16, 15]. The sensitivity of the temperature with respect to the placement speed and laser power was investigated in [14] for tape laying of continuous carbon fiber reinforced PEEK laminates.

The temperature distribution along the length and through the thickness of the flat composite laminate during a tape laying process was predicted in [13]. The tape lay-up processing speed, nozzle exit temperature, and cooling rate were found to be the major process variables. The effects of preheating the consolidated flat laminate, temperature distributions and thermal histories were investigated for varying consolidation speeds and the overall feasibility of the proposed process was discussed in [17].

Further studies employed a combined optical-thermal model for the LATP process in [12, 6]. A ray tracing approach was implemented to estimate the heat flux distribution on the tape and substrate. It was shown in [12, 6] that there was a shadow region which caused a significant temperature drop immediately prior to the nip point. More advanced heat flux description was introduced in [30, 7] by incorporating non-specular laser reflections from the tape, substrate and roller in an optical process model. The scattering reflectance behavior of a unidirectional thermoplastic prepreg tape was formulated in [30] through a developed bidirectional reflectance distribution function (BRDF) model for LATW and LATP processes. A micro half cylinder (MHC) approach was presented in [7] to simulate the scattering of laser irradiance via a commercial software (OptiCAD10) for a flat substrate in the LATP process. Both approaches enabled capturing the shadow regions of the tape and substrate prior to the nip point where the input laser heat flux cannot be received. The same optical model reported in [7] was used in [36] to include the laser power distribution in a two-dimensional (2D) thermal analysis performed by a commercial finite element package Ansys. The tape and substrate temperature distributions were studied comprehensively.

Next to the numerical modeling studies focusing on the LATP processes on flat tooling as in [12, 6, 7, 36], optical-thermal models for curved coolings were developed in [82, 39, 32, 35] by the current authors. The laser radiation on circular surfaces was investigated in [39] based on a three-dimensional (3D) ray tracing optical model combined with a 1D through-thickness thermal model. The effect of non-specular reflections on the process temperature was studied for different laser power distributions. A 3D optical model was presented in [35] to consider the effect of out-of-plane winding on the substrate and tape temperatures in the LATW process. The effect of different winding orientations on the nip point temperature was studied in [32] for curved geometries.

The mentioned combined optical-thermal process models achieved a realistic temperature prediction, however, they only dealt with modeling discontinuous winding/placement on either flat or curved geometries. The lack of in-depth numerical optical-thermal models for continuous LATW processes on curved geometries still leads to unwanted temperature variations as shown in Figure 4.2. One of the most important aspects not covered comprehensively by the current models is the influence of the previously deposited layer's temperature on

the nip point temperature when a new layer is deposited during continuous LAWTLATP processes.

The objective of the present work is to critically analyze the temperature evolution near the nip point during continuous LATW processes by means of a comprehensive computational model. The focus is on the process modeling of adjacent hoop winding of a type-IV pressure vessel made of G/HDPE composite. A fully or two-way coupled local and global process models is introduced for the process simulation of continuous LATW processes. More specifically, a local optical-thermal model is combined with a global thermal model to incorporate the global cooling and local heat accumulation as described in Figure 4.2 [26]. The conducted experiments of three consecutive rounds of adjacent hoop winding from current authors in [26] are used as the basis of this paper for validating the developed process model. After validating the model with the measured tape and substrate temperature distributions, the effect of liner radius size on the peak temperature and gradual cooling/heating behavior is addressed by the developed process model for continuous LATW processes. The performed experiments by current authors are briefly discussed in Section 2. The local optical-thermal and global thermal models are presented in Section 3.

The local optical-thermal and global thermal models are part of the comprehensive OTOM (Optical Thermal Optimization Model) simulation tool developed by using MATLAB at the University of Twente for the simulation of the LATW/LATP processes.

The optical model includes a generic 3D ray tracing model to simulate the laser intensity distribution on the tape and substrate surfaces. The local thermal model comprises a 2D/3D fully implicit transient advection-diffusion thermal model to calculate the temperature distribution of the tape and substrate near the nip point. The global thermal model employs a 2D heat conduction model to calculate the temperature of the pressure vessel during the cooling period, i.e. non-irradiated locations. The obtained results are discussed in Section 4. The final part of the paper presents the conclusions and recommendations for further research in Section 5.

4.2 Experimental Work

The continuous adjacent hoop winding of pressure vessels experimentally studied by current authors in [26] was the basis of the present process modeling. The summarized process of adjacent hoop winding of the pressure vessel is depicted in Figure 4.3 from the neat thermoplastic liner to adjacent hoop winding procedure and then finished adjacent hoop winding (left to right). The prepreg tapes were made of G/HDPE with 47% fiber volume content and the liner was made of pure HDPE with pigments. A schematic view of the

continuous LATW process for winding of three rounds is depicted in Figure 4.4. The length (L_L) and radius (R_L) of the cylindrical part of the liner were 640 mm and 136 mm, respectively. The winding angle (θ) was set to 88.2° to obtain proper layers adjacently wound. Total of 22 layers were adjacently wound for each round, i.e. Round-1, Round-2 and Round-3 as seen in Figure 4.4. The winding of a single layer took approximately 6.2 s corresponding to approximately 135 s for each round. The layers of Round-1 were started and ended at point O1 and O2, respectively, as illustrated schematically in Figure 4.4. A deformable roller was used to consolidate the incoming prepreg tape with the substrate locally. An infrared thermographic camera was utilized to measure the temperature on the tape and substrate surfaces during the continuous hoop winding process. Further details can be found in [26].

Fig. 4.3 Adjacent hoop winding on a neat 40-liter blow-molded HDPE type-IV composite pressure vessel via LATW process performed by the Fraunhofer IPT. In this picture (from left to right), the neat thermoplastic liner, adjacent hoop winding procedure and then finished hoop winding tank liner are represented.

4.3 Modeling of continuous LATW process

A local optical-thermal process model domain was developed near the nip point to predict the substrate and tape temperatures. On the other hand, a global thermal model was employed to predict the cooling of the substrate after the nip point as well as the heating of the roller and the air inside the pressure vessel. The process simulation of the continuous adjacent hoop winding of FRTPCs therefore followed a fully coupled local optical-thermal and global thermal modeling procedure in the present work. The flowchart of the process modeling framework is presented in Figure 4.5.

The corresponding equations are also represented in this figure to clarify flow of the implemented method.

The laser irradiation was calculated by the optical model and the obtained heat flux distribution was transferred to the local thermal model. The heat loss in the substrate after the nip point was calculated using the global thermal model and the updated substrate

temperature was used as a boundary condition (BC) in the local thermal model. Similarly, the time dependent temperatures of the roller and air inside the vessel were updated in the global thermal model and transferred to the local thermal model as a BC. This coupling was done when the local thermal domain passed the calculation points defined for each layer as shown in Figure 4.4. This procedure was applied for three rounds of adjacent hoop winding with a total process time of approximately 405 s. The details of the optical, local and global thermal models are presented in the following.

Fig. 4.4 A schematic view of the continuous LATW process for winding of three rounds consisting of 22 adjacent layers. The unfolded representation of the cylindrical shaped liner is shown on the right.

Fig. 4.5 The flowchart of the coupled local optical-thermal and global thermal modeling approach for the process simulation of continuous LATW of FRTPCs. The corresponding equations are also shown.

4.3.1 Optical model

The optical model compromises the liner, roller, incoming prepreg tape and substrate which were defined in a 3D global coordinate system as a reference. Each object in the global axis system had its own local coordinate system. A schematic view of the 3D optical model domain is seen in Figure 4.6. The deformable roller was assumed to have a contact with the liner at the line N_1 - N_2 and C_1 - C_2 , respectively. N_1 - N_2 was defined as the nip line. The tape-roller contact was defined by the angle λ . A 3D ray tracing approach was implemented in the optical model as indicated in Figure 4.7(a). Here, $\mathbf{I}_i$ was the i^{th} incoming ray defined as a 3D line, $P_i(X, Y, Z)$ was the intersection point of $\mathbf{I}_i$ with substrate, $\mathbf{n}_i$ was the surface normal, β_i was the incident angle, $\mathbf{r}_i$ was the 3D reflected ray and $P_{i,ref}(X, Y, Z)$ was the intersection point of $\mathbf{r}_i$ with the tape. The defined incoming rays can collide with multiple surfaces, e.g. tape (indicated as ray-a in Figure 4.7(a)), roller (ray-b) and substrate in the optical model. A top-hat laser power distribution with a divergence angle of γ as seen in Figure 4.7(b) was considered. The laser divergence was considered as 4 degrees in the simulations [26, 77]. A 3D representation of the corresponding reflections from the defined objects is shown in Figure 4.7(c). The incoming rays were assumed to reflect specularly in the current model to prevent high computational cost.

Fig. 4.6 Schematic view of the 3D optical model domain consisting of liner, roller, tape and substrate geometry.

The procedure used on the optical model started with irradiating diverged rays from the laser cross-sectional plane with dimensions $H_L \times W_L$. Based on the preliminary convergence

Fig. 4.7 a) Schematic view of the roller indentation (δ), the ray-tracing approach with incoming ray and reflection for tape (ray-a), substrate ($\mathbf{I}_i$) and roller (ray-b). b) Laser source divergence definition represented as γ . c) A 3D representation of the incoming rays and reflected rays from liner, substrate, tape and roller.

study, the total number of rays used in the optical model was 9600 (120 along the length and 80 along the height of the laser source plane). The rays were distributed uniformly along the length and width directions of the laser plane aligned with the laser optic direction as shown in Figure 4.7(c). The intersection points of each incoming/reflected rays defined as a 3D line with the objects (liner, roller, tape and substrate), e.g. $P_i(X,Y,Z)$ were calculated analytically as described by Langford in [93]. According to the intersection point, the surface normal $\mathbf{n}_i$ and the incident angle β_i of the i^{th} ray were determined. The 3D reflected ray $\mathbf{r}_i$ was obtained using the expression in Equation 4.1:

$$\mathbf{r}_i = 2(\mathbf{I}_i \cdot \mathbf{n}_i)\mathbf{n}_i - \mathbf{I}_i \quad (4.1)$$

Similarly, the intersection point of $\mathbf{r}_i$ with another parametric surface, i.e. $P_{i,ref}(X,Y,Z)$, together with $\mathbf{n}_{i,ref}$ and $\beta_{i,ref}$ were calculated. The irradiation power distributions on the objects were calculated based on the obtained intersection points of rays/reflections with objects via the ray tracing approach. The irradiation power distribution of the i^{th} ray Φ_i , was calculated by dividing the total laser power P_{laser} by the total number of rays N_{ray} . The

conservation of the energy was maintained by considering:

$$\Phi_i = \phi_{i,a} + \phi_{i,r} \quad (4.2)$$

where $\phi_{i,a}$ and $\phi_{i,r}$ were the the absorbed and reflected energy at the intersection point $P_i(X, Y, Z)$, respectively. Here, the transmitted energy was neglected similar to conducted analyses in [94, 30]. $\phi_{i,a}$ was calculated using the following expression:

$$\phi_{i,a} = \Phi_i F_i(n_i, \beta_i) \quad (4.3)$$

where $F_i(n_i, \beta_i)$ was the fraction of the absorbed energy calculated by using the unpolarized Fresnel equations [95, 30] and n_i was the refractive index. Similarly, the absorption of the reflected energy $\phi_{i,r}$ at point $P_{i,ref}(X, Y, Z)$ was calculated using $\phi_{i,a,ref} = \phi_{i,r} F_{i,ref}(n_{i,ref}, \beta_{i,ref})$. This approach was successively continued for the total number of rays and reflections until all intersection points of the incoming rays and corresponding energy were calculated. Note that only one reflection was considered in the optical model as similarly conducted in [94, 33] because the energy carried by the second and following reflected rays were estimated as less than 5% of the energy of the incoming ray [39]. In the present work, it was assumed that all optical phenomena took place at the irradiated surfaces and all non-reflected light was therefore considered to be absorbed. Thus, the imaginary part of the complex refractive index was not considered in this study as also done in [30] The roller deformation was also taken into account in the current optical model. The roller was moved towards the mandrel vertically with a value of $\vec{\delta}$ as shown in Figure 4.7(a) for the sake of simplicity. The resulting geometry and the intersection points of the roller with the substrate (N_1 - N_2 and C_1 - C_2) were considered in the optical model.

4.3.2 Local thermal model

The local thermal model employed the optical model output (power intensity distribution) as a heat flux boundary condition (see Figure 4.5). A schematic view of the local thermal model domain for the tape and substrate is given in Figure 4.8. The curved tape and substrate geometries defined in the optical model were unfolded to the computational domains seen in Figure 4.8 in order to handle the numerical implementation in an easy manner. Since the incoming tape thickness was relatively thin and remained constant during the process, a 2D thermal domain was used for the tape. On the other hand, a 3D thermal model was employed for the substrate in order to account for the thickness increase during the continuous winding process of three rounds as illustrated in Figure 4.4. The corresponding transient heat

conduction equations for the tape and substrate are given in Equation 6.1 and Equation 6.2, respectively:

$$\rho C_p \left(\frac{\partial T}{\partial t} + v \frac{\partial T}{\partial x} \right) = k_x \left(\frac{\partial^2 T}{\partial x^2} \right) + k_y \left(\frac{\partial^2 T}{\partial y^2} \right) \quad (4.4)$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + v \frac{\partial T}{\partial x} \right) = k_x \left(\frac{\partial^2 T}{\partial x^2} \right) + k_y \left(\frac{\partial^2 T}{\partial y^2} \right) + k_z \left(\frac{\partial^2 T}{\partial z^2} \right) \quad (4.5)$$

where v was the feeding velocity of the tape showing the material movement toward the nip line (N_1 - N_2), C_p was the specific heat, ρ was the density, x, y, z represented the local spatial locations, k_x, k_y, k_z represented the thermal conductivity in the x -, y -, z -direction, respectively, t was the time and T was the temperature. The applied BCs are shown in Figure 4.8. The heat flux distribution obtained from the optical model (Q_{ir}) was defined at the tape surface and the top of the substrate surface, i.e. $z = 0$ by mapping the intersection points of the laser rays with the thermal calculation points. More specifically, a mapping procedure was applied in order to translate the laser irradiation from the optical points to the control volumes in the thermal model. The energy of each incoming ray defined in the optical model was distributed among the four closest control volumes in the thermal model based on the distance between the intersection point of the ray and corresponding control volume where the temperature was calculated at the center. Q_{ir} was defined as the absorbed energies from all rays and reflections

($\phi_{i,a}$ and $\phi_{i,a,ref}$). A heat transfer coefficient (HTC) of h_{RT} with the average roller temperature T_{roller} was defined at the roller-tape interface contact, i.e. at $0 < x < \pi R_R(\lambda/180)$. The remaining surface of the tape, i.e. at $\pi R_R(\lambda/180) < x < L_T$, and the top of the substrate surface at $z = 0$ were exposed to the ambient air temperature $T_{air} = 20^\circ\text{C}$ with a HTC of h_{air} . Note that T_{roller} was updated in the global thermal model in order to take the heating of the roller. The inlet temperature of the tape was set to 20°C at $x = L_T$, i.e. line B_1 - B_2 . On the other hand, the inlet temperature distribution for the substrate was set to $T_{incoming}$

(defined as incoming material temperature in the local thermal model)

at $x = L_S$, i.e. the surface containing the line A_1 - A_2 in Figure 4.8. The heat transfer between the substrate and the air inside the pressure vessel was defined by h_{air} with the average air temperature inside the vessel T_{inner} at $z = th_S$ where th_S was the substrate thickness. By using the global thermal model T_{roller} and T_{inner} were updated based on the global heat transfer at the tape-roller and substrate-liner interfaces. Adiabatic thermal BC was applied to the remaining boundaries of the tape and substrate computational domains. The initial temperature condition was set to 20°C for both calculation domains including T_{roller} , $T_{incoming}$ and T_{inner} .

The control volume based finite difference method was employed to solve the governing equations with the upwind implicit scheme as described in [96, 97]. A structured control volume based mesh was employed using the local coordinate system (x, y, z) . Total of 40×23 control volumes were used in the x - and y -direction, respectively, for the tape and $30 \times 23 \times 14$ control volumes in the x -, y - and z -direction, respectively, for the substrate.

Tape (2D): Local thermal model

Substrate (3D): Local thermal model

Fig. 4.8 Schematic view of the local thermal model domains for the tape and the substrate which were unfolded from the optical domain defined in Figure 4.6. The applied boundary conditions are also indicated.

4.3.3 Global thermal model

The global thermal model employed the predicted tape and substrate temperature distributions from the local thermal model. Accordingly, the cooling of the substrate as well as the heating of the roller and the air inside the pressure vessel were estimated. A schematic view of the global thermal model is depicted in Figure 4.9. The calculation domains are illustrated in Figure 4.9(*left*) during winding of a single layer which can also be seen in Figure 4.4(*right*). Each calculation point which was located on the liner had a unique temperature history. Heat conduction was allowed between the tape and substrate at the nip line N_1 - N_2 at which the calculated tape and substrate temperature distributions were combined. In order to make the global model computationally fast, in-plane heat conduction in the winding direction was neglected. The main reason for this was the fact that the through-thickness heat conduction and surface boundary conditions dominate the thermal problem as analyzed and assessed critically in [6]. Besides, the heat conduction rate is much smaller than the rate at which the laser moves. The resulting 2D cross section is seen in Figure 4.9(*right*) and the corresponding

governing equation is given as:

$$\rho C_p \left(\frac{\partial T}{\partial t} \right) = k_y \left(\frac{\partial^2 T}{\partial y^2} \right) + k_z \left(\frac{\partial^2 T}{\partial z^2} \right) \quad (4.6)$$

The applied BCs are shown in Figure 4.9(right). Convective heat transfer was defined at the top surface of the cross-sectional domain ($z = 0$) for *i*) the roller from time $t_{0,i}$ to $t_{1,i}$ and *ii*) for the ambient air from time $t_{1,i}$ to $t_{2,i}$, as indicated in Figure 4.9(right) for the i^{th} layer. Since all input process parameters were assumed constant in the current example, the sampling points indicated as *i* in Figure 4.9(left) were defined along the liner length seen in Figure 4.4. A total of 50 points was determined for which a total of 50 2D cross-sectional domains seen in Figure 4.9(right) were utilized. When the local thermal domain was at a global calculation point, $T_{incoming}$ in the local thermal model was updated accordingly, e.g. the temperature distribution at $t_{2,i}$ was used for $T_{incoming}$ in the local thermal model. A total of 23×14 control volumes was used in the *y*- and *z*-direction, respectively. The increase in the average air temperature inside the liner (T_{inner}) due to continuous heating of the liner during winding of three adjacent layers was estimated using the relation [98]:

$$\rho^{air} V^{air} C_p^{air} \frac{\Delta T_{inner}}{\Delta t} = A_{AL} h_{air} (T_{liner} - T_{inner}) \quad (4.7)$$

where T_{liner} was the average temperature at the bottom of the substrate (at $z = th_S + th_T$), ΔT_{inner} was the increase in T_{inner} during a time step of Δt , ρ^{air} was the air density, V^{air} was the inside pressure vessel volume as 40 liter, A_{AL} was the contact area between air and the liner which was $2\pi R_L L_L$ in the global model and C_p^{air} was the specific heat of the air inside the liner with the air at ambient pressure of 1 atm. . Similarly, the increase in average roller temperature T_{roller} was estimated by using the expression:

$$\rho^R V^R C_p^R \frac{\Delta T_{roller}}{\Delta t} = A_{RT} h_{RT} (T_{tape} - T_{roller}) + Q_R^{ir} \quad (4.8)$$

where T_{tape} was the average tape temperature in contact with the roller, A_{RT} was the contact area between tape and the roller which was equal to $W_T \pi R_R (\lambda/180)$, ΔT_{roller} was the increase in T_{roller} during a time step of Δt , ρ^R was the silicon roller density, V^R was the roller volume, C_p^R was the specific heat of the roller and Q_R^{ir} was the total power exerted on the roller due to the irradiating laser rays and reflections to the roller (see intersection of rays and reflections with the roller in Figure 4.7c)). The effect of the roller cooling system was not significantly effective on the silicone part of the deformable roller as it was observed during

the experiments [26]. Thus, the cooling system effect on the roller temperature estimation was neglected in the process model.

Fig. 4.9 Representation of the calculation domains together with the side-view of time-position relation in the global thermal model (*left*) and the considered 2D cross-sectional domain with the employed boundary conditions (*right*).

4.4 Process model parameters and case studies

The geometrical parameters used in the optical and thermal models were defined based on the experimental work in [26] and are listed in Table 6.1. A wider substrate control volume than tape width was considered in the process model which was also the case in the thermographic images. The tape feeding velocity was 140 mm/s. The laser distribution at the laser source had a uniform power distribution with a total power of 900 W. The material properties utilized in the process modeling are given in Table 6.2. Since the temperature-dependent material properties of the HDPE tape and liner were not known and in order to clearly understand the continuous characteristic (location- and time-dependent) of the adjacent hoop LATW process, constant thermal material properties were considered as also used in [6, 99]. The refractive index of the prepreg tape was assumed as 1.8 as in [6]. The refractive index of HDPE polymer liner was taken from [100] as 1.5. The higher refractive index indicates a lower absorption of the incoming laser rays by the material. In addition, the effect of mandrel size on the process temperature evolution was studied for two other mandrel radii of 272 mm and 68 mm (default radius was 136 mm [26]).

Table 4.1 Geometrical parameters considered in the optical and thermal models.

Geometrical parameters	Symbol	Values	Unit
Laser source dimensions (see Figure 4.6)	W_L, H_L	14, 28 [26]	[mm]
Laser source distance w.r.t. nip point (see Figure 4.7)	S_1, S_2	370, 210 [26]	[mm]
Laser source angle w.r.t. nip point (see Figure 4.7)	θ_L	29.5	
Width of tape	W_T	25	[mm]
Thickness of tape	th_T	0.25	[mm]
Roller radius	R_R	45	[mm]
Length of flat part of tape	L_{T-flat}	100	[mm]
Length of tape	L_T	110	[mm]
Degree of tape-roller contact	λ	50.0	
Substrate length	L_S	85	[mm]
Width of substrate control volume	W_S	30	[mm]
Initial substrate (liner) thickness	th_S	4.0	[mm]
Liner radius	R_L	136	[mm]
Liner cylindrical length	L_L	640	[mm]
Roller width	W_R	35	[mm]
Winding angle	θ	88.2	
Maximum divergence angle	γ	4	
Roller indentation	$\vec{\delta}$	2.4	[mm]

4.5 Results and discussion

4.5.1 Process model predictions

The laser intensity distributions on the tape and substrate surfaces were first predicted using the optical model and the results are shown in Figure 4.10 for Round-1 and Round-2. The maximum power intensity was obtained

far away from the nip line as indicated in Figure 4.10

for the selected incident angles of the incoming and reflected laser rays. The maximum value of the power intensity was estimated approximately as $3.2 \times 10^{-1} \text{ W/mm}^2$ for the tape and substrate. The total power absorbed by the pure HDPE liner (Round-1) and substrate (Round-2) was calculated as 487.65 W and 465.7 W, respectively. The decrease in the power from Round-1 to Round-2 was due to the increase in the substrate refractive index from that of the liner to that of the wound UD tape. This resulted in a subsequent increase in the total power (272.85 W to 286.5 W) received by the tape due to the increase in laser reflections from the substrate to the tape. The power distribution of Round-3 was almost the same as Round-2 for the tape and substrate since the substrate refractive index remained the same.

Table 4.2 Material properties used in the optical and thermal model.

Parameters	Symbol	Values	Unit
Tape thermal conductivity	k_x	0.98 [73]	[W/(m-K)]
	$k_y = k_z$	0.72	[W/(m-K)]
HDPE liner thermal conductivity	k_{liner}	0.45[101]	[W/(m-K)]
Tape density	ρ	1710 [73]	[kg/m ³]
HDPE liner density	ρ	955 [101]	[kg/ m ³]
Tape specific heat	C_p	1180 [73]	[J/(kg-K)]
HDPE liner specific heat	C_p	2200[101]	[J/(kg-K)]
Air specific heat	C_p^{air}	718[98]	[J/(kg-K)]
Air density inside liner	ρ^{air}	1.225	[kg/ m ³]
Silicone roller density	ρ_p^R	2180 [102]	[kg/ m ³]
Silicone roller specific heat	C_p^R	710 [103]	[J/(kg-K)]
Roller refractive index	n_R	1.43 [36]	-
(G/HDPE) tape prepreg refractive index	n_{tape}	1.8 [6]	-
HDPE liner refractive index	$n_{substrate}$	1.5 [100]	-
Air HTC*	h_{air}	10 [12]	[W/(m ² -K)]
Roller HTC*	h_{RT}	500 [14]	[W/(m ² -K)]

*(heat transfer coefficient)

The corresponding predicted temperature distributions by the local thermal model are depicted in Figure 4.11 for Round-1, Round-2 and Round-3. Note that the square boxes indicated on the tape and substrate were the locations at which the temperature was measured during the process in [26]. These boxes were defined at the centerline of the tape and substrate and 10 mm prior to the visible nip line M_1 - M_2 . It is seen that the substrate temperature was approximately 150C, 180C and 200C at the visible nip line (M_1 - M_2) for Round-1, Round-2 and Round-3, respectively. The increase in the substrate temperature from Round-1 to Round-2 was mainly due to the previously wound hot tape and increase in air temperature inside the liner. Similarly, the tape had a higher temperature near the visible nip line M_1 - M_2 which was mainly due to the increase in roller temperature and a larger contribution of laser reflections from the substrate going from Round-1 to Round-2 as explained above. Further tape and substrate temperature increases in Round-3 were due to continuing heat accumulation in the liner and roller. The evolution of the substrate temperature at the middle of the actual nip line N_1 - N_2 was used as schematically illustrated in Figure 4.12 to evaluate the temperature history of the previously wound tape. The general trends of the cooling behavior of the center point of the actual nip line seen in Figure 4.12 are depicted in Figure 4.13 for points O1, O2 and O3 as an example. It is seen that when the laser head came back to point O1 at $t = 270$ s,

the previously wound tape temperature was approximately 50C which was higher than the initial temperature of 20 C due to the increase in the air temperature inside the liner.

Accumulation of the thermal energy from the wound tapes of the previous round was the reason for this temperature increase.

In addition, there was an approximately 200C increase in substrate temperature for point O2 at $t = 135$ s and approximately 190C for point O1 at $t = 270$ s due to the winding of two consecutive layers from Round-1 to Round-2 and from Round-2 to Round-3, respectively. The difference between the temperature increase, i.e. increase of 200C for point O2 versus 190 C for point O1, was due to the different substrate thickness in Round-1 and Round-2. The exemplary temperature distributions predicted in the global thermal model for point O3 at $t = 68$ s when the laser head just passed and at $t = 201$ s just before the laser head passed are also given in Figure 4.13. A detailed analysis of the process temperature distribution and evolution is given in the following.

Fig. 4.10 Simulation contour of absorbed power intensity distribution (optical model output) on the tape and substrate in adjacent hoop winding at: (a) Round-1, (b) Round-2. The total absorbed energy by the tape and the substrate are indicated as well. (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Fig. 4.11 Local thermal model output: The predicted contour plots of the temperature distribution on the tape and substrate surface during continuous winding of Round-1, Round-2 and Round-3. The presented results were extracted during winding of layer-11 (see Figure 4.4). Here, M_1 - M_2 is the visible nip line by the thermal camera and N_1 - N_2 is the actual nip line which is at the back side.

Fig. 4.12 Schematic of the locations at which the temperature evolution was reported using the global thermal model.

4.5.2 Analysis of the process temperature - comparison with experiments

The predicted local temperature distribution shown in Figure 4.11 was compared with the thermographic images measured by the thermal camera in [26] which are depicted in Figure 4.14². A good agreement between the measured and predicted local temperature distribution was obtained for Round-1 and Round-2.

The maximum difference in mean temperature between the experiments and simulations was found to be approximately 3% and 10% for tape and substrate, respectively.

A more detailed comparison between the predicted and measured temperature distributions was made by extracting the temperature values along the length and width direction as seen in Figure 4.15 and Figure 4.16, respectively. A total of 20 thermographic frames

²Since there was no thermographic image data recorded during manufacturing of Round-3 in [26], only the simulation results were represented for this round.

Fig. 4.13 *Top*: The evolution of the average substrate temperature at the actual nip line at points O1 (layer 1), O2 (layer 22) and O3 (layer 11) during winding of three rounds. *Bottom*: Exemplary temperature distributions for point O3 at $t = 68$ s after the laser head passed in Round-1 and at $t = 201$ s before the laser head passed in Round-2.

from the experimental measurements at the middle of Round-1 and Round-2 was extracted of which the mean values and corresponding standard deviations were shown.

The extracted frames were obtained from the thermographic recorded video with 50 frames per second (50 Hz) to investigate the main trends of the temperature history as described in [26].

The temperature distributions at the centerline along the length or winding direction are depicted in Figure 4.15. Overall a good agreement was found between the predicted and measured temperature distributions. The increase in the tape and substrate temperature at the center of the nip line (M_1 - M_2) was captured by the proposed process model. More specifically, the tape temperature at the nip line increased approximately by 15°C from Round-1 to Round-2 and by 7°C from Round-2 to Round-3. A larger increase in substrate temperature was found at the center of the nip line which was approximately 42°C from Round-1 to Round-2 and 30°C from Round-2 to Round-3. The temperature distributions along the width direction at the nip line are plotted in Figure 4.16.

Overall, the process model predictions were found to be close to the measured temperature range and profiles for Round-1 and Round-2. The predicted substrate temperature for

Round-2 was found to be lower than the measured temperature which could be due to the simplifications made in the process model such as employing constant optical-thermal material properties and neglecting the geometrical disturbances that existed in the winding process as described in [26].

It is seen that there was a temperature gradient across the width directions which was mainly due to the winding angle. The temperature difference for tape and substrate across the width at M_1 - M_2 was approximately 10C.

In addition to the temperature distributions, the evolution of the average temperatures within the measurement box (see Figure 4.11 and Figure 4.14) for tape and substrate are shown in Figure 4.17. It is seen that there was a good match between the predicted and measured temperature for tape and substrate. The tape temperature followed a relatively simple profile since the heat convection in the control volume of the tape was constant through the process except for the heat transfer with the roller. The roller temperature calculated in the global thermal model was found to increase from 20°C to approximately 130C at the end of Round-3 which slightly increased the tape temperature. The mean tape temperature was approximately 125C in Round-1 and 145C at the end of Round-3. A small jump in the tape temperature occurred at point O2 of approximately 10 °C that can be ascribed to the increase in reflected energy from the substrate related to the difference in the substrate refractive index of the HDPE liner (Round-1) and the wound tape (Round-2) as explained before. The developed process model also captured the overall experimental trend and peak values of the substrate temperature very well. A steady substrate temperature at around 125 °C was predicted for Round-1 in line with the experimental trend. The effects of the accumulated heat of previously wound tapes, the increases of the roller temperature and the air temperature inside the liner as well as the contribution of global cooling were more pronounced in Round-2 and Round-3. There were jumps in the substrate temperatures at the beginning of Round-2 and Round-3 in both experiment and simulations with an amount of approximately 80-120C. These temperature jumps are very important since high temperatures could potentially degrade the material and deteriorate the final product quality. The reason for the temperature jumps was the longer exposure to the laser heating due to reversal of the translational movement of the winding head (see kinematics in Figure 4.4) at the end of each round, inherent to the consecutive nature of the process. A gradual substrate temperature decrease was observed within Round-2 and Round-3 due to heat loss to the ambient through convection as also seen in Figure 4.13. The heat transport to the air inside the liner led to an increase of the air temperature up to approximately 65 °C at the end of Round-3, which explains why the substrate temperature developments of subsequent rounds move up to higher temperature values. The predicted substrate temperature reached approximately 160C

at the end of Round-2, i.e. approximately a 50°C decrease from the peak temperature of 210°C. This decrease in temperature was with approximately 40 °C (from approximately 240 °C to 200 °C) in Round-3 about 10 °C smaller than in Round-2, which can be ascribed to the higher air temperature within the liner in Round-3 decreasing the effectiveness of the heat loss.

The higher liner air temperature along with the incorporated heat of previously hot wound tapes (the substrate from Round-1 and Round-2) were also the main reasons for a slight increase in the predicted substrate temperature of approximately 5 °C at point O2 from $t = 135$ s at the start of Round-2 to $t = 405$ s at the end of Round-3.

Fig. 4.14 Measured temperature distributions on the tape and substrate surface during continuous winding of Round-1 and Round-2 [26]. The presented results were extracted during winding of layer-11 (see Figure 4.4).

4.5.3 Effect of pressure vessel size

The effect of pressure vessel radius (R_L) on the evolution of process temperature was analyzed using the proposed process model. The developments of the average temperature within the measurement box for $R_L = 68$ mm, $R_L = 136$ mm and $R_L = 272$ mm are shown in Figure 4.18. A slight increase in the tape temperatures as a function of the liner diameter can be observed, for example, from 0 to 60 s in Figure 4.18(*left*). The increase can be ascribed to a stronger contribution of laser light reflection by the less curved substrate. The tape temperature gradually increased during continuous winding of three rounds for every liner radius due to the continuous increase in the roller temperature. At the end of Round-3 the tape temperature was already close to 170 °C.

The substrate temperature decreases as a function of the liner diameter as can be observed in Figure 4.18(*right*), see for example the range from 0 to 60 s. The larger the substrate

Fig. 4.15 Predicted and measured tape (*left*) and substrate (*right*) temperature profiles at the centerlines of the surfaces along the winding direction, i.e. along the x -direction seen in Figure 4.8.

Fig. 4.16 Predicted and measured tape (*left*) and substrate (*right*) temperature profiles at the centerlines of the surfaces along the width direction, i.e. along the y -direction seen in Figure 4.8.

radius the lower the temperature level at which the substrate temperature develops over time. When more laser light is reflected from the substrate to the tape, as described above, less heat remains for the substrate, explaining the altered temperature developments. However, two more aspects play a role here explaining the lower substrate temperatures. Firstly, the volume of the vessel liner increases with the liner radius leading to a slower heating of the air inside the vessel. Secondly, a larger vessel needs more time to be covered by tape, which means that the cooling time is increased if the tape winding speed is maintained constant. The peak

Fig. 4.17 Predicted and measured tape (*left*) and substrate (*right*) temperatures near the nip point during continuous adjacent hoop winding of three rounds of G/HDPE composites based on Figure 4.4.

temperatures at point O2 at the end of Round-1 and at point O1 at the end of Round-2 were also strongly affected by the liner radius. More specifically, the average peak temperature at point O1 went up to approximately 254 °C for $R_L = 68$ mm at the indicated box location which was prior to the nip line (see also Figure 4.11). This indicated that the temperature at the nip line was even larger than 254 °C as can also be inferred from the substrate temperature development for $R_L = 136$ mm in Figure 4.15(*right*), where the temperature maintains a raising trend towards the nip line N_1 - N_2 . On the other hand, the substrate peak temperature was approximately 209 °C for $R_L = 272$ mm. Thus, the process parameters need to be optimized based on the local geometry of the liner to keep the temperature within a desired range.

4.6 Conclusions and outlook

This study was performed in order to critically asses the temperature evolution during the continuous LATW process. A fully coupled local and global process models was developed based on the type-IV pressure vessel manufacturing experiment performed in [26]. Unidirectional G/HDPE tapes were continuously wound through adjacent hoop winding on an HDPE liner. The laser power intensity distributions were calculated by the 3D optical model for the tape and substrate illuminated by the laser. Differences in the refractive index of the substrate's HDPE liner and the wound tape had a significant influence on the power intensity distributions. The local temperature distribution near the nip point was captured by

Fig. 4.18 Predicted tape (*left*) and substrate (*right*) temperature evolutions near the nip point for different pressure vessel radii. The duration of the winding process is proportional to the liner radius at constant winding speed.

the thermal model. The global cooling and heating of the pressure vessel was estimated by the global thermal model. The predictions of the process temperature distributions and evolution on the tape and substrate surfaces were found to agree quite well with the experimentally measured temperatures in [26].

The effects of the heat accumulated during winding of the vessel liner by a number of layers and the gradual increase in roller and air temperature inside the liner on the process temperature were found to be very important to predict the continuous temperature evolution and possible temperature peaks. The variation in the substrate temperature was found to be more severe than the tape temperature mainly due to local overheating of the substrate at locations where the translational movement of the winding head changed direction, i.e. from Round-1 to Round-2 and from Round-2 to Round-3. Here, a temperature increase of approximately 80-120 °C was found to take place for the substrate when two layers of prepreg tape were wound consecutively. This increase was much lower for the tape with values up to 10 °C. Besides the studied LATW process simulations based on the experimental work in [26], the influence of pressure vessel size on the tape and substrate temperatures was investigated for different liner radii.

The peak substrate temperature was found to increase approximately 45°C by reducing the radius of the pressure vessel from $R_L = 272$ mm to $R_L = 68$ mm. The temperature increase was mostly caused by (i) the shorter time it took to complete the winding process of a smaller vessel, leaving less time for cooling and (ii) the smaller volume of air inside the vessel that was heated up more easily.

It was observed that even with constant input parameters, a complex processing temperature evolution was obtained as a function of time, location and local liner geometry. Thus, the heat flux obtained from the optical model needs to be optimized via the laser power distribution as a future work to achieve a desired process temperature in each round. In addition, the development of a more comprehensive statistical ray tracing approach is considered as a future work. To have an even more accurate process model, the experimental characterization of the roller deformation, optical and thermal material properties as a function of surface topology, temperature and fiber orientation is required. Nevertheless, the fulfilled work within this paper has already the potential to eliminate expensive trial and error based experiments through the physics-based process simulations that are well capable of predicting the major trends in the time and spatial temperature distributions of the tape and the substrate as a function of process conditions.

Chapter 5

Optical and thermal effects of winding angle, mandrel curvature and tape width on processing zone

¹ Advanced thermoplastic composites manufacturing using laser assisted tape placement or winding (LATP/LATW) is a challenging task as monitoring and predicting nip point (bonding) temperature are difficult especially on curved surfaces. A comprehensive numerical analysis of the heat flux and temperature distribution near the nip point is carried out in this paper for helical winding of fiber reinforced thermoplastic tapes on a cylindrically shaped mandrel. An optical ray-tracing technique is coupled with a numerical heat transfer model in the process simulation tool. The developed optical-thermal model predictions were compared with experimental data available in literature to validate its effectiveness. The influences of winding/placement angle, mandrel curvature and tape width on the incident angles, the laser absorbed intensity, and the process temperature distribution are studied extensively using the validated model. Winding/placement angle has a considerable effect on the temperature distribution. Increase in winding angle results in a higher temperature for tape due to more reflections coming from the substrate. On the other hand, substrate temperature decreases as the winding angle due to a decrease in the laser incident angles based on the local surface curvature. An increase in mandrel curvature results in higher nip point temperatures for substrate and lower one for tape. Different mandrel sizes for 90° placement path do not have a strong effect on the substrate process temperature as for other winding angles because of less

¹This chapter was part of "A.Z., I.B., T.C.B. and R.A., 3D Numerical Modeling of Laser Assisted Tape Winding Process of Composite Pressure Vessels and Pipes-Effect of Winding Angle, Mandrel Curvature and Tape Width, in Materials, June 2020, DOI.org/10.3390/ma13112449". A.Z. developed and performed numerical simulation methods and wrote main structure of the paper, I.B. and T.C.B. provided critical review, and R.A. contributed to the methodology and supervision of research.

curvature change of the corresponding irradiated area. Tape width causes local temperature variations at the edges of the tape/substrate. In order to obtain the desired process temperature during LATW or LATP processes, the laser intensity distribution on the tape and substrate surfaces should be regulated.

5.1 Introduction

Laser assisted tape placement (LATP) is an automated manufacturing process to produce fiber reinforced thermoplastic composite structures. The out-of-autoclave potential of the LATP method together with its automation possibilities make it attractive for aerospace and automotive industries. The LATP method is also suitable for winding of prepreg fiber reinforced thermoplastic tapes on a cylindrical liner/mandrel via the laser assisted tape winding (LATW) process to manufacture composite parts such as pipes for oil and gas industry or hydrogen storage pressure vessels for the transportation industry.

Figure 5.1a schematically shows the LATP/LATW process method in which the fiber reinforced thermoplastic tape is placed onto a mandrel and/or a composite substrate. Figure 5.1b illustrates an image of a hoop winding/placement on a metal mandrel. The incoming tape and substrate are heated using a laser and bonded under the application of a pressure exerted by a compaction roller. An in-situ consolidation can be achieved by a proper adjustment of the applied heat, pressure and process speed. The temperature of the nip point at which the tape and substrate are bonded plays a critical role together with the consolidation pressure and time for having proper intermolecular diffusion and healing of the thermoplastic matrix. The importance of process parameters on the mechanical performance and bonding quality was shown extensively in References [104, 99, 105–107, 6]. A proper understanding and description of the laser irradiation and reflection which determine the temperature distribution near the nip point is therefore crucial for in-situ consolidation using LATP and LATW processes. The role of absorption and reflection of the laser irradiation by the material was also illustrated in Reference [108] during a powder bed fusion process. The composite tape has an angle-dependent laser absorption and reflection which make the LATP and LATW processes very challenging to control especially for manufacturing on curved surfaces. In addition, the variation in material, geometrical and process parameters causes a variation in the bonding temperature [26]. Therefore, maintaining the nip point temperature at desired values is needed to obtain a proper consolidation and adhesion between the subsequent layers [62].

Fig. 5.1 Description of the laser assisted tape placement or winding (LATP/LATW) method and its elements including laser optics, substrate, tape, roller and mandrel. The hoop winding/placement process where thermoplastic tape and substrate are preheated by the laser source and the tape is pressed on the substrate at the nip point location through a consolidation roller are shown as: **(a)** Principle, **(b)** System technology (detailed view on the experimental set-up employed at Fraunhofer IPT, Aachen, Germany).

Several studies in literature investigated the temperature evolution and distribution during LATP and LATW processes experimentally and computationally. Thermal models were developed in [11–14, 16, 15, 17, 109, 90, 92, 91] by assuming a uniform heat flux exerted on the substrate and tape for the sake of simplicity in numerical process modeling. An analytical thermal solution of the LATP process on a flat tooling was developed in Reference [11] in which the through-thickness temperature distribution was investigated at high process speeds. A significant drop in temperature prior to the nip point was found in [12] due to the presence of a shaded region originated from the roller geometry. The effects of variation in material properties, thickness and fiber volume fraction on the substrate temperature were studied statistically in Reference [66] for the LATW of AS4/PEEK composites. A two dimensional (2D) thermal model was coupled with a crystallization model in References [16, 15] and the influence of process parameters on the crystallization was studied. The sensitivity of the temperature with respect to the winding/placement speed and laser power was investigated in Reference [14] for tape laying of continuous reinforced carbon fiber (CF)/PEEK laminates. The effects of processing parameters on processability in on-line consolidation of thermoplastic composites was studied in Reference [109] for tape-laying and filament-winding processes employing anisotropic thermal analyses. The results showed that the heater size, preheating conditions and tow thickness affected the processing window significantly. The analysis in Reference [13] predicted the temperature distribution along the length and through the thickness of the flat composite laminate during a tape laying process.

The tape lay-up processing speed, nozzle exit temperature and cooling rate were found to be the major process variables. The effects of preheating the consolidated flat laminate, temperature distributions and thermal histories were investigated for varying consolidation speeds and the overall feasibility of the proposed process was discussed in Reference [17].

The absorption and reflection behavior of the composite material during the LATP and LATW processes were taken into account in References [6, 30, 7]. More specifically, dedicated optical models which determined the heat flux distribution as an output variable were developed in order to couple it with thermal models for having a better prediction of the temperature distribution near the nip point. A specular reflection model was used in Reference [6] for LATP on flat surfaces by incorporating a 2D ray-tracing method which was combined with a 1D thermal model in the through-thickness direction. The anisotropic optical behavior of the tape and substrate was described using a bidirectional reflectance distribution function (BRDF) in Reference [30] for the circular winding/placement cases. A micro half cylinder (MHC) approach was presented in Reference [7] to simulate the laser irradiance scatter via a commercial software (OptiCAD 10) in the LATP process on a flat substrate or tool. The temperature predictions using the coupled optical-thermal process models for the LATP in Reference [6] revealed that the incident flux distribution on the substrate decreased rapidly near the nip point due to the shadowing effect of the roller. The same optical model developed in Reference [7] was used in Reference [36] to predict the laser power distribution in the 2D thermal analysis of LATP on flat surfaces using the commercial finite element software package ANSYS. The variations of tape and substrate temperature using different assumptions for the laser divergence modeling were reported.

Besides the thermal phenomena investigated for the LATP processes on flat tools or substrates, the LATW of relatively simple non-flat geometries was studied for the case of ring winding in References [110, 39]. The through-thickness temperature evolution in the substrate made of CF/PEEK was quantified in Reference [110]. The BRDF was used in a 3D ray-tracing model coupled with a 1D heat transfer model in Reference [39] to predict the temperature distribution for different process parameters in LATW of circular CF/PEEK composites. The influence of different laser power distributions on the nip point temperature was studied in Reference [39]. Although there have been several studies carried out to describe the temperature distribution in the LATP and LATW process of fiber reinforced thermoplastic composites, a critical assessment of the helical winding/placement on cylindrical mandrels, for example, for composite pipe and pressure vessel manufacturing, has not been considered. The laser irradiation and reflection determining the heat flux distribution on curved surfaces inherently contains a complexity due to the variation in the incident angle of the laser light with respect to the winding/placement angle and curved surface

geometry [32, 35]. In addition, the interaction of rays and reflections with the substrate and tape can vary as the tape/substrate width changes. In Reference [28], it was clearly stated that overheating of the tape or substrate affected the intralaminar void content, intralaminar bond strength and residual stress negatively. Besides, an insufficient bonding may take place if the temperatures near the nip point are below those within the processing window. These aspects need to be analyzed comprehensively in order to develop optimum process conditions to maintain a constant nip point temperature during the process.

In the present work, the influence of the winding/placement angle, the mandrel diameter and the tape width on the temperature distribution near the nip point is numerically investigated for the helical LATP/LATW process of fiber reinforced thermoplastic composites as a part of the EU funded project. The optical and thermal models are part of the comprehensive OTOM (Optical Thermal Optimization Model) simulation tool developed by using MATLAB at the University of Twente for the simulation of LATW/LATP processes. A generic 3D optical model is developed based on a ray-tracing technique incorporating the varying incident angles due to the helical path curvature on the mandrel. The predicted heat flux distributions obtained from the optical model are used in a 2D and 3D numerical thermal model for tape and substrate, respectively, in order to predict the temperature distributions. The coupled optical-thermal process model is validated by comparing the predicted temperature evolution with available literature data for the LATP process using a flat tooling. The validated model is subsequently applied to the LATP/LATW process on non-flat tooling and the behavior of the absorbed laser power intensity distribution is described based on the surface curvature of the tooling, the winding/placement angle and the tape width. The variations in the incident angle of incoming rays and reflections on the substrate and tape are analyzed quantitatively. The characteristics of the temperature distribution as well as the total absorbed energy from the direct laser hit and reflections are studied for helical winding/placement of tapes on different curved surfaces, that is, different mandrel diameters.

5.2 Optical Model

A parametric 3D optical model based on the ray-tracing approach was developed for LATP and LATW processes using an in-house code written in MATLAB. A schematic view of the model geometry is seen in Figure 6.5a. A global coordinate system denoted as X, Y and Z was used in the optical model. Here, W_R and R_R were the roller width and radius, respectively, W_L and H_L were the width and height of the laser source defined as a plane, respectively. A top-hat laser power distribution with a divergence angle of γ was considered [77]. The

winding/placement angle θ , the substrate width W_S and the tape width W_T were assumed to be constant during the manufacturing process.

Fig. 5.2 (a) Geometry of the parametric 3D optical model. (b) Schematic of ray-tracing approach with incoming ray and reflection for tape (ray-a), substrate ($\mathbf{F}_i$) and roller (ray-b). (c) Schematic of the laser divergence angle γ which is maximum at the edges and linearly decreases to 0° at the center of laser source.

The winding/placement direction along which the roller moved to deposit the unidirectional tape on the substrate was defined by θ . The substrate was therefore oriented on the mandrel (tooling) in the direction defined by the θ . The substrate domain on the cylindrical mandrel was calculated as a function of mandrel radius R_M , W_S and θ using a closed form solution:

$$X_{path} = R_M \sin\left(\eta \frac{\sin(\theta)}{R_M}\right) + R_M \sin\left(\xi \frac{\cos(\theta)}{R_M}\right), \quad 0 < \eta < W_S, 0 < \xi < L_S \quad (5.1)$$

$$Y_{path} = R_M \cos\left(\eta \frac{\sin(\theta)}{R_M}\right) + R_M \cos\left(\xi \frac{\cos(\theta)}{R_M}\right), \quad 0 < \eta < W_S, 0 < \xi < L_S \quad (5.2)$$

$$Z_{path} = \eta \cos(\theta) + \xi \sin(\theta), \quad 0 < \eta < W_S, 0 < \xi < L_S, \quad (5.3)$$

where L_S was the substrate length, ξ and η were variables of substrate width and length for defining curved substrate locations denoted as $X_{path}, Y_{path}, Z_{path}$ (based on right-hand axis system of the mandrel at its center). Executing these equations in the optical model, different substrate orientations on the mandrel can be generated. The contact region between the tape and roller was defined with the angle θ_R . A schematic representation of the generic 3D ray-tracing approach is seen in Figure 6.5b. The position of the laser source, that is, the location $P_L(X,Y,Z)$ and orientation θ_L , was defined with respect to the nip line N_1-N_2 at which the origin of the global optical coordinate system was located. A total of N_{ray} rays was used to model the laser power distribution. Each incoming laser ray was defined as a 3D line which is represented as $\mathbf{F}_i$ for the i th ray in Figure 6.5b. The intersection point of $\mathbf{F}_i$ with a 3D parametric surface, for example, $P_i(X,Y,Z)$, was determined analytically and the

corresponding surface normal $\mathbf{n}_i$ and the incident angle β_i were calculated. The 3D reflected ray $\mathbf{r}_i$ was obtained using the expression $\mathbf{r}_i = 2(\mathbf{F}_i \cdot \mathbf{n}_i)\mathbf{n}_i - \mathbf{F}_i$. Similarly, the intersection point of $\mathbf{r}_i$ with another parametric surface, for example, $P_{i,ref}(X, Y, Z)$, together with $\mathbf{n}_{i,ref}$ and $\beta_{i,ref}$ were calculated. The defined rays can collide with multiple surfaces, for example, the tape (indicated as ray-a in Figure 6.5b), the roller (ray-b), the substrate and the mandrel in the optical model.

A representation of the simulation model showing the placement angles of 0° , 30° , 45° , 60° and 90° is shown in Figure 5.3. In all cases, the relative orientation and location of the laser cross-section plane toward the nip-point were remained constant. However, the relative locations of the points on substrate toward the laser plane were changed due to the curvature. This effect can strongly change the absorbed energy intensity and the process temperature as a result of changes in the irradiated area and the irradiation angle. The intersection points of incoming rays with the 3D surfaces for $\theta = 0^\circ$, $\theta = 45^\circ$ and $\theta = 90^\circ$ are illustrated in Figure 5.4a–c, respectively. It is seen that the curvature of the mandrel and the laser divergence were taken into account in the developed model. The corresponding intersection points of the reflected rays with substrate, tape, mandrel and roller are shown in Figure 5.4d for $\theta = 45^\circ$, as an example. The incoming rays were assumed to reflect specularly in the current model for the sake of simplicity (ease of analysis) and computational time.

The rays were discretized uniformly along the length and width of the laser source plane. The irradiation power distribution of the i th ray, Φ_i , was calculated by dividing the total laser power P_{laser} by N_{ray} . The conservation of the energy was maintained by considering:

$$\Phi_i = \phi_{i,a} + \phi_{i,r}, \quad (5.4)$$

where $\phi_{i,a}$ and $\phi_{i,r}$ were the the absorbed and reflected energy at the intersection point $P_i(X, Y, Z)$, respectively. Here, the transmitted energy was neglected. $\phi_{i,a}$ was calculated using the following expression:

$$\phi_{i,a} = \Phi_i F_i(n_i, \beta_i), \quad (5.5)$$

where $F_i(n_i, \beta_i)$ was the fraction of total energy calculated by using the unpolarized Fresnel equations [95, 30] and n_i was the refractive index. Similarly, the absorption of the reflected energy $\phi_{i,r}$ at point $P_{i,ref}(X, Y, Z)$ was calculated using $\phi_{i,a,ref} = \phi_{i,r} F_{i,ref}(n_{i,ref}, \beta_{i,ref})$. This approach was successively continued for the total number of rays and reflections until all intersection points of the incoming rays and corresponding energy were calculated. Note that only one reflection was considered in the optical model because the energy carried by the second and following reflected rays were estimated as less than 5% of the energy of the incoming ray [39]. The total number of rays used in the optical model was 32 k (160 along

optical model is represented in Figure 5.5.

referred to the web version of this article).

Fig. 5.4 Intersection of the incoming rays with the mandrel, the tape, the substrate and roller for (a) $\theta = 0^\circ$, (b) $\theta = 45^\circ$ and (c) $\theta = 90^\circ$. (d) The corresponding intersection of the reflected rays for $\theta = 45^\circ$.

Fig. 5.5 Flowchart of the optical model.

5.3 Thermal Model

A local thermal model was developed by employing the control volume based finite difference technique in order to predict the temperature distribution prior to the nip line (N_1 - N_2 in Figure 6.5a). The generic tape and substrate geometries defined in the optical model were unfolded to the computational domains in the thermal model as shown in Figure 6.7. A local coordinate system denoted as x, y and z was employed in the thermal model. A structured control volume based mesh was therefore defined in the local (x, y, z) coordinate system. The thickness of the incoming tape is usually very thin as compared to the substrate thickness which yields a uniform temperature distribution in the through-thickness direction for the tape. Therefore, 2D and 3D heat conduction models were considered for generic purposes for the tape and substrate, respectively. The advection term in the heat transfer equation was implemented using a Eulerian frame work. The corresponding governing equations given in Equations (6.1) and (6.2) for the tape and substrate, respectively, were solved using an upwind implicit scheme as described in Reference [97].

$$\rho C_p \left(v \frac{\partial T}{\partial x} \right) = k_x \left(\frac{\partial^2 T}{\partial x^2} \right) + k_y \left(\frac{\partial^2 T}{\partial y^2} \right), \quad \text{Tape} \quad (5.6)$$

$$\rho C_p \left(v \frac{\partial T}{\partial x} \right) = k_x \left(\frac{\partial^2 T}{\partial x^2} \right) + k_y \left(\frac{\partial^2 T}{\partial y^2} \right) + k_z \left(\frac{\partial^2 T}{\partial z^2} \right). \quad \text{Substrate} \quad (5.7)$$

Fig. 5.6 Schematic view of the thermal domains for tape and substrate which were unfolded from the optical domain defined in Figure 6.5.

In Equations (6.1) and (6.2), T was the temperature, v was the winding/placement velocity of the tape showing the material movement toward the nip line, C_p was the specific heat, ρ was the density, x, y, z represent the local spatial locations, k_x, k_y, k_z were the coefficient of thermal conductivity of the composite material in x -, y - and z -direction, respectively. Thermal properties were assumed to be independent of the temperature in the current research as also considered in References [6, 99]. In order to show the finite difference implementation, the equation in Equation (6.2) as a general 3D case was discretized for an exemplary interior control volume denoted as i, j, k along the x -, y - and z -direction, respectively in Equation (5.8).

$$\rho C_p \left(v \frac{T_{i,j,k} - T_{i-1,j,k}}{\Delta x} \right) = k_x \left(\frac{T_{i+1,j,k} - 2T_{i,j,k} + T_{i-1,j,k}}{\Delta x^2} \right) + k_y \left(\frac{T_{i,j+1,k} - 2T_{i,j,k} + T_{i,j-1,k}}{\Delta y^2} \right) + k_z \left(\frac{T_{i,j,k+1} - 2T_{i,j,k} + T_{i,j,k-1}}{\Delta z^2} \right), \quad (5.8)$$

where $\Delta x, \Delta y$ and Δz were the distance between the control volumes in x -, y - and z -direction, respectively. The formulation in Equation (5.8) was transformed to a matrix notation and assembled for m number of total control volumes which can be represented as:

$$[K]\{T\} = \{Q\}, \quad (5.9)$$

where $[K]$ was the $m \times m$ thermal conductivity matrix, $\{T\}$ was the $m \times 1$ temperature vector and $\{Q\}$ was the $m \times 1$ thermal load vector.

The following boundary conditions were employed in the thermal domains as illustrated in Figure 6.7:

Tape (2D):

$$\pm \left(k_x \frac{\partial T}{\partial x} + k_y \frac{\partial T}{\partial y} \right) = q_{ir} + h_{air}(T - T_{air}) \quad \text{for} \quad (L_T - L_{T,flat}) < x < L_T, -W_T/2 < y < W_T/2 \quad (5.10)$$

$$\pm \left(k_x \frac{\partial T}{\partial x} + k_y \frac{\partial T}{\partial y} \right) = q_{ir} + h_R(T - T_{roller}) \quad \text{for} \quad 0 < x < L_{T,flat}, -W_T/2 < y < W_T/2 \quad (5.11)$$

$$\frac{\partial T}{\partial x} = 0 \quad \text{at} \quad x = 0 \quad (5.12)$$

$$T = T_{incoming} \quad \text{at} \quad x = L_T \quad (5.13)$$

$$\frac{\partial T}{\partial y} = 0 \quad \text{at} \quad y = -W_T/2, W_T/2. \quad (5.14)$$

Substrate (3D):

$$\pm k_z \frac{\partial T}{\partial z} = q_{ir} + h_{air}(T - T_{air}) \quad \text{at} \quad z = 0 \quad (5.15)$$

$$\pm k_z \frac{\partial T}{\partial z} = h_{tooling}(T - T_{tooling}) \quad \text{at} \quad z = th_S \quad (5.16)$$

$$\frac{\partial T}{\partial x} = 0 \quad \text{at} \quad x = 0 \quad (5.17)$$

$$T = T_{incoming} \quad \text{at} \quad x = L_S \quad (5.18)$$

$$\frac{\partial T}{\partial y} = 0 \quad \text{at} \quad y = -W_S/2, W_S/2, \quad (5.19)$$

where q_{ir} was defined as the heat flux generated in the optical model considering the absorbed and reflected energies ($\phi_{i,a}$ and $\phi_{i,a,ref}$), h_{air} , $h_{tooling}$ and h_R were the heat transfer coefficient of air, tooling (mandrel) and roller, respectively, T_{air} , $T_{tooling}$, T_{roller} and $T_{incoming}$ were the air, tooling (mandrel), roller and incoming material temperature, respectively. The thermal model convergence was checked concerning the advection term used in the steady-state heat conduction equation. Based on the preliminary convergence study, the total number of control volumes was determined as 600 (40 and 15 in the x - and y -direction, respectively) for the tape and 9000 (40, 15 and 15 in the x -, y - and z -direction, respectively) for the substrate.

Since the number of rays defined in the optical model was larger than the control volumes defined on the tape and substrate surface (at $z = 0$), a mapping procedure was defined in order to translate the laser irradiation from optical points to the control volumes in the thermal model. The energy of each incoming ray defined in the optical model was distributed among the four closest control volumes in the thermal model based on the distance between the intersection point of the ray and corresponding control volume using the expression in

Equations (5.20) and (5.21):

$$w_j = \frac{\frac{1}{d_j}}{\frac{1}{d_1} + \frac{1}{d_2} + \frac{1}{d_3} + \frac{1}{d_4}}, \quad (j = 1, 2, 3, 4) \quad (5.20)$$

$$\phi_i = w_1\phi_i + w_2\phi_i + w_3\phi_i + w_4\phi_i, \quad (5.21)$$

where d_j was the distance between the intersection point of the i th ray and j th control volume within the closest four control volumes, w_j was the corresponding weighting function and ϕ_i was the total absorbed energy by the tape or substrate. This procedure is schematically illustrated in Figure 5.7 and was carried out for the whole tape and substrate domains. The flowchart of the described thermal model in this section is represented in Figure 5.8.

Fig. 5.7 Distribution of the exemplary absorbed energy (ϕ_i) inside the thermal domains (Ω for the substrate, Ω' for the tape).

Fig. 5.8 Flowchart of the implemented thermal model.

5.4 Model Parameters and Case Studies

The developed optical-thermal model was utilized to simulate the LATP process of CF/PEEK composites reported in References [12, 36] for verifying the numerical implementation. Subsequently, various case studies for the LATP and helical LATW processes were performed. In LATW processes, usually, the linear velocity is incorporated which is translated from the angular velocity and the lateral movement of the laser head. Therefore, a linear velocity was assumed for all the cases in this work. The geometrical parameters used in the process simulations are listed in Table 6.1. The corresponding material and process parameters are given in Table 6.2. The unidirectional GF/HDPE (glass fiber high density polyethylene) thermoplastic tape [73] was employed in the present work aligning with the EU funded amblifibre project objectives with the focus on manufacturing low-cost thermoplastic products. The composite properties were estimated using a rule of mixture [111] based on the fiber volume content of the GF/HDPE which was 47% [73]. Note that the average values of the temperature dependent material data (ρ , C_p , k_x , k_y and k_z) provided in References [12, 36] were used in the present work for the model validation.

In order to study the effect of curved surface geometries and θ on the temperature distributions, different case studies were carried out using the model parameters listed in Table 5.3. It is seen that three different tape/substrate sizes (denoted as Ref, Wide-T and Narrow-T) were considered with three different mandrel sizes (denoted as Ref, Big-M and Small-M) for the helical LATW process. A total of five winding/placement angles was

used for each case. Only $\theta = 0^\circ$ was considered for the LATP process with three different tape/substrate sizes. The total number of process simulations performed in the case studies was 28.

Table 5.1 Geometrical parameters used in the current modeling work and model validation based on the available data in References [12, 36] according to the schematic geometrical model domain given in Figure 6.5.

Geometrical Parameters	Symbol	LATW/LATP Current Work (Ref.)	LATP [12] (Validation)	LATP [36] (Validation)	Unit
Laser location(X,Y)	P_L	200, 16	200, 84	171.6, 98.1	[mm]
Laser source width	W_L	40	16 *	16 **	[mm]
Laser source height	H_L	50	45 *	45 **	[mm]
Laser source angle	θ_L	11.8	22.7	32	[°]
Laser divergence angle	γ	4 [77]	N/A	3	[°]
Tape width	W_T	25 [73]	12	12	[mm]
Tape thickness	th_T	0.25 [73]	0.15	0.15	[mm]
Roller radius	R_R	45	32	40	[mm]
Roller width	W_R	50	50	40	[mm]
Length of flat part of tape	$L_{T,flat}$	78	55	50	[mm]
Length of tape-roller contact	θ_R	50.0	50	67.4	[°]
Substrate length	L_S	150	120	90	[mm]
Substrate width	W_S	30	30	25	[mm]
Substrate thickness	th_S	0.25	3.48	1.65	[mm]
Mandrel radius	R_M	136	∞	∞	[mm]
Winding/placement angle	θ	0–90	0	0	[°]

* at distance of 127 mm from the laser source aperture, ** at distance of 200 mm from the laser source aperture.

Table 5.2 Process and material properties used in the current modeling work and model validation based on the available data in References [12, 36].

Process/Material Parameters	Symbol	GF/HDPE (Current Work)	CF/PEEK [12] (Validation)	CF/PEEK [36] (Validation)	Unit
Composite thermal conductivity	k_x, k_y, k_z	0.85, 0.65, 0.65 [73]	5.9, 0.7, 0.7	5.9, 0.7, 0.7	[W/(m-K)]
Composite density	ρ	1750.0 [73]	1575	1575	[kg/m ³]
Composite specific heat	C_p	1220.0 [73]	1500	1500	[J/(kg-K)]
Winding/placement linear velocity	v	100	133	100	[mm/s]
Total laser power	P_{laser}	2500	1100 (assumed)	1130	[W]
Air heat transfer coefficient	h_{air}	10 [6]	10	10	[W/(m ² -K)]
Air temperature	T_{air}	20	20	20	[°C]
Roller heat transfer coefficient	h_R	100 [6]	500	500	[W/(m ² -K)]
Roller temperature	T_{roller}	20	100	50	[°C]
Tooling heat transfer coefficient	$h_{tooling}$	100 [6]	∞	∞	[W/(m ² -K)]
Tooling temperature	$T_{tooling}$	20	20	20	[°C]
Incoming material temperature	$T_{incoming}$	20	20	20	[°C]
Composite refractive index	n_c	1.95 [36]	1.95	1.95	-
Roller refractive index	n_R	1.43 [36]	1.43	1.43	-

Table 5.3 Summary of the case studies performed using the developed parametric optical-thermal model.

Case Studies	R_M [mm]	W_T [mm]	W_S [mm]	θ [°]	Total Simulations
Flat	∞	12.5, 25, 38	15, 30, 38	0	3
Reference (Ref)	136	25	30	0, 30, 45, 60, 90	5
Big mandrel (Big-M)	272	25	30	0, 30, 45, 60, 90	5
Small mandrel (Small-M)	68	25	30	0, 30, 45, 60, 90	5
Wide tape (Wide-T)	136	38	38	0, 30, 45, 60, 90	5
Narrow tape (Narrow-T)	136	12.5	15	0, 30, 45, 60, 90	5

5.5 Result and Discussion

5.5.1 Process Model Validation

The tape and substrate temperature distributions prior to the nip line/point were predicted using the proposed optical-thermal model for the LATP process reported in References [12, 36] and the results are shown in Figure 5.9. It is seen from Figure 5.9 that the predicted temperature distributions at the centerline of the tape and substrate along the winding/place-ment direction agreed well with the reported ones in References [12, 36]. The discrepancy between the predicted and reported tape temperatures was due to the differently implemented modelling approaches. More specifically, the tape was modelled as a 2D domain considering the x - z plane using the finite element method in Reference [12], whereas the x - y plane seen in Figure 6.7 was employed with a control volume based finite difference approach in the present work. Another source of tape temperature difference, which was also valid for the substrate, was due to the constant thermal material properties in the current model and temperature-dependent one in Reference [36]. However, both tape models resulted in very similar cooling rates and shadowed regions at the nip point with the temperature of approximately 500 °C–520 °C. The length of the shadowed regions on the substrate was found to be approximately 4 mm and 6 mm for the configurations reported in Reference [12] and Reference [36], respectively. The corresponding predicted substrate temperatures at the nip point were found to be approximately 470 °C and 300 °C. Although a 2D computational domain, that is, x - z plane seen in Figure 6.7, was used for the substrate in References [12, 36], similar laser irradiation lengths and temperature evolutions were obtained using the 3D optical-thermal model for the substrate. The details of the optical model output are discussed in detail in the following.

Fig. 5.9 Tape and substrate temperature results from Reference [12, 36] and corresponding results from the developed present simulation model. The temperature of a particle through the time from laser irradiation until nip point is shown.

5.5.2 Case Studies

Optical Analysis

The main outcome of the 3D optical model was the absorbed power intensity distribution on the tape and substrate. The obtained distributions for the cases Flat and Ref using different θ are shown in Figure 5.10 by unfolding the respective 3D surfaces into 2D ones. The slight scatter in the intensity distribution in Figure 5.10 was mainly due to the utilized finite number of laser rays that originated from the discretized laser source. Nevertheless, the sufficient number of rays were used in the optical model which provided converged temperature output in the thermal model in which the finite difference method was employed. It is seen in Figure 5.10 that the intensity distributions on the tape surfaces were almost identical for different winding/placement configurations which was as expected because the laser orientation was in parallel with the tape and the tape geometry remained constant for all simulations. The slight differences, for example, for $\theta = 30^\circ, 45^\circ, 60^\circ$, were due to the reflections from the substrate. The total irradiation length of the tape was approximately 60 mm and the region 20 mm prior to the nip line was not heated, that is, the so-called shadow area, due to the curvature of the tape that is in contact with the roller as seen in Figure 6.5. The effect of the mandrel curvature on the intensity distribution was found to be more significant for the substrate. A more non-uniform and non-symmetric intensity distribution was predicted especially for $\theta = 30^\circ, 45^\circ, 60^\circ$ due to more complex laser irradiation and reflections. The shadow region for the substrate was found to occupy a smaller area as compared with the shadow regions for the tape. In addition, the reflections coming from the roller as well as the laser divergence also played a role on the intensity distribution on the substrate as can be understood from the slight reduction in the intensity magnitude at the edges, that is, at $y = -12.5$ mm and $y = 12.5$ mm (see Figure 5.10). The length of the

heated region reduced approximately from 140 mm to 75 mm as θ reduced from 90° to 0° , as expected from Figure 5.4. On the other hand the magnitude of the intensity increased with a decrease in θ due to an increase in the incident angle β . The effect of the laser divergence angle γ can be seen for Flat and Ref- 90° cases in which the laser intensity magnitude was slightly smaller near the nip line region than the region far away from the nip line. A gradual decrease in the intensity magnitude was found towards the nip line for $\theta = 0^\circ, 30^\circ, 45^\circ, 60^\circ$ mainly due to a decrease in β . The reflections on the substrate surface coming from the tape and roller were also visible, for example, the region approximately 50–60 mm away from the nip line for Flat and Ref- 90° cases. The maximum laser intensity value on the substrate was calculated as 0.35 W/mm^2 for $\theta = 0^\circ$.

Fig. 5.10 Absorbed power intensity distribution on the tape and the substrate for the cases Flat and Ref ($W_T = 25 \text{ mm}$ and $W_S = 30 \text{ mm}$) using different θ . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

The heat flux distributions on the substrate and tape surfaces were determined by the incident angle β of the incoming and reflected rays as well as by the illuminated (and heated) area by the incoming and reflected rays. The mean of β for each case study listed in Table 5.3 was calculated using the optical model and the obtained results are shown in Figure 5.11. It is seen that the mean of β is always smaller than 45° for the incoming rays and the mean of

β is always larger than 45° for the reflected rays for both tape and substrate. It was found that β for the incoming rays of the substrate gradually decreased from a range of 25° – 45° to a constant value of 14° with an increase in θ from 0° to 90° , mainly due to the change in the surface curvature. The decrease in β was the most significant for the case Small-M due to a greater curvature, leading to much higher values of β . On the other hand, β of the incoming rays on the tape remained almost the same at approximately 42° since the tape geometry was not changed with θ . In addition, the incoming rays with relatively high β values covered a larger area on the tape than the substrate. This resulted in a larger heated area on the tape surface with higher laser intensity distribution which can be seen from Figure 5.10 as well. There was a gradual increase in the mean of β for the reflected rays of the substrate coming from the tape and roller with an increase in θ due to the fact that a larger amount of reflected rays hit the substrate surface. Similarly, the tape received larger amounts of reflected rays as θ decreased because a larger amount of rays reflected towards the ambient environment and not to the tape when θ decreased. This can also be seen from the heat flux distribution for the case Ref displayed in Figure 5.10 such that at $\theta = 90^\circ$ locally a higher intensity is approximately between 60 mm–70 mm before the nip line as compared with 0° for the tape. The corresponding total absorbed powers by the substrate and tape for each case are shown in Figure 5.12. It is seen that the total power absorbed by the substrate gradually decreases with an increase in θ mainly due to a reduction in the mean β . On the other hand, this trend was found to be the opposite for the tape, although the mean of β remained the same. The reason behind this was the increase in the intensity of illuminated or heated area for the tape by the number of reflected rays coming from the substrate as θ increased. The case Wide-T had the largest absorbed total power for the substrate and tape since the heated area was the largest for this case. The influence of the mandrel size on the power intensity distribution of the substrate is illustrated in Figure 5.13. It is seen that a more localized power intensity distribution occurred for the Small-M due to higher laser incident angles on the substrate. This localized behavior on the Small-M which took place near the nip line caused a smaller heat loss from the irradiation location until the nip line via the convection than the corresponding heat loss of the Big-M.

Fig. 5.11 The mean of β distribution on the substrate and tape surfaces for each case study listed in Table 5.3.

Fig. 5.12 The total absorbed power for the substrate and tape calculated based on the incoming and reflected energies for each case study listed in Table 5.3.

Fig. 5.13 Effect of substrate curvature due to the mandrel diameter on the laser irradiated area and its absorbed power intensity on the case Ref-0° for: (a) Small-M, (b) Big-M (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

The overview of the corresponding contribution for the total absorbed power from the incoming and reflected rays is shown in Figure 5.14 for the case Ref and Flat as an example. It is seen that up to 20% of the absorbed power was from the reflected rays for the tape with $\theta = 90^\circ$ and it was approximately 12% for the $\theta = 0^\circ$. It was even slightly more for the Flat case than for Ref-90° as the substrate surface gradient was more toward the tape. The absorbed power by the substrate from the reflected rays was approximately 12%–18%.

Fig. 5.14 The distribution of the total absorbed power based on the incoming and reflected rays for case Ref and Flat with different θ .

Thermal Analysis

The predicted temperature distributions on the tape and substrate surfaces are shown in Figure 5.15 for the case Ref and Flat. The more localized absorbed laser intensity on the tape due to the reflections from the substrate resulted in higher temperature values which can be seen in Figure 5.15 for the cases Flat, Ref-90° and Ref-60°. The substrate temperatures increased with a decrease in θ due to an increase in the laser incident angle and stronger light absorption. On the other hand, the tape temperature decreased with a decrease in θ because less reflections from the substrate to the tape took place for lower θ values with respect to the winding/placement curvature. The temperature at the nip line was found to vary between 200 °C–250 °C for the tape and 160 °C–220 °C for the substrate. The higher tape temperature as compared with the substrate was mainly due to the higher incident angle of the tape (see Figure 5.11) as also discussed in Section 5.5.2.

Fig. 5.15 Predicted temperature distribution on the tape and the substrate for the cases Flat and Ref ($W_T = 25$ mm and $W_S = 30$ mm) using different θ . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

The temperature distributions at the nip line were further investigated in detail for each case study since the nip line temperature played an important role on the bonding quality of

the tape and substrate as aforementioned. To illustrate, the temperature distribution along the nip line is shown in Figure 5.16 for each case with $\theta = 90^\circ$ and $\theta = 60^\circ$. It is seen that there is a temperature variation along the nip line for the tape and substrate mainly due to mandrel curvature, laser divergence, laser reflections from tape and roller, that is, the tape had a larger refractive index than the roller. This effect can be easily distinguished for the cases Narrow-T and Wide-T where Narrow-T had more reflections from the roller than Wide-T.

Fig. 5.16 Temperature distribution at the nip line for each case at $\theta = 90^\circ$ (left) and 60° (right). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

The effects of reflections from the roller on the substrate were observed from the temperature distributions for Wide-T and Narrow-T at $\theta = 90^\circ$, that is, the substrate temperatures at the edges were lower for Narrow-T than Wide-T due to a smaller amount of reflected energy from the roller in the Narrow-T case. Therefore, the Wide-T case yielded higher substrate temperatures with an amount of approximately 5°C increase at the edges of the substrate. The influence of θ on the temperature variation at the nip line was more significant which resulted in a reduction in the temperature at one of the substrate/tape edges by approximately 20°C as seen in Figure 5.16 (right). The mandrel curvature affected the nip line temperature variation by approximately 15°C for $\theta = 60^\circ$. The means and standard deviations of the temperature variations at the nip line are summarized in Figure 5.17. It is seen that the Big-M case resulted in higher tape temperatures than the Small-M case which was due to a stronger reflection contribution from the substrate to the tape. The other way around was the case for the substrate, that is, lower temperatures were obtained for the Big-M case as compared with the Small-M case due to smaller laser incident angles for the larger mandrel. The effect of θ on the mean nip line temperature can be easily seen in Figure 5.17 for the tape and substrate. The standard deviation of the substrate temperature was found to be higher than of the tape which was due to the mandrel curvature. The largest standard deviation of the substrate

temperature distribution was approximately 4.7 °C for $\theta = 60^\circ$ for the case Ref which resulted in a coefficient of variation of 2.5%. The corresponding maximum coefficient of variation was approximately 1.3% for the tape temperature obtained for $\theta = 60^\circ$ of the Small-M.

Fig. 5.17 Average temperatures of the tape and substrate and corresponding standard deviations at the nip line for each simulation case as a function of selected θ values.

The emerged tape and substrate temperature variation along the nip line especially for $\theta = 30^\circ$, 45° and 60° should be kept between certain material-dependent upper/lower temperature bounds in order to have proper consolidation quality which can be controlled by an optimized laser intensity. The temperature variations based on θ , mandrel size and tape width as summarized in Figure 5.17 are very critical since an overheating might take place for the tape on a higher θ and a low-melting temperature at the same time might be the case for the substrate. This is a challenge for the power intensity distribution as the laser source should provide a controllable energy distribution between the tape and substrate for different process conditions. Optimizing the laser settings such as the laser direction, the laser location or the laser distribution with the goal of desired temperature distribution is therefore essential to keep the tape and substrate temperatures at the desired levels.

5.6 Conclusions

In this research, a generic combined optical-thermal model of the LATP/LATW processes was presented to predict the temperature development of the tape and the substrate for helical paths on cylindrically shaped mandrels. The developed optical-thermal model was first validated successfully with available literature data of the LATP on flat tooling. Subsequently, the influences of the winding/placement angle, mandrel radius and tape/substrate width on the absorbed laser intensity and the corresponding temperature distributions on the tape and the substrate were investigated. The relations between the incident angle of the incoming/re-

flected laser rays and total absorbed absorbed power were quantified using the optical model. The temperature distributions on the substrate and tape surfaces as well as on the nip line were analyzed critically using the thermal model. The variations in temperature with respect to different winding/placement angles, mandrel sizes and tape widths were analyzed systematically. The following conclusions from the validated model can be drawn:

An increase in the winding/placement angle resulted in higher temperatures for the tape and lower for the substrate. The increase in tape temperatures was approximately 30°C–40°C and decrease in substrate temperatures was approximately 40°C–50°C. More contribution from reflections from the substrate for higher θ values resulted in higher tape temperatures. On the other hand, lower substrate temperatures were obtained with larger incoming laser incident angles for lower θ values. Similarly, higher substrate temperatures were the case for the mandrel with relatively small diameter (Small-M) due to larger incident angles. A reduction in tape temperature was found for this mandrel size because some of the reflections from the substrate did not illuminate the tape. The tape and substrate temperatures were found to be less sensitive to a change in tape/substrate width as compared with the winding/placement angle and the mandrel diameter. However, the tape/substrate width effect on the tape and substrate temperature was manifested through a crescent temperature profile along the nip line where temperature variations occurred mainly at the edges of the tape and substrate.

The detailed analysis conducted in this paper showed the importance of the relation between the mandrel surface curvature and tape/substrate temperature for different geometrical configurations of the processing zone. The demonstrated opposing behavior of the total absorbed power and nip line temperature of the tape and substrate is very important especially in order to prevent temperature variations, overheating or having too low temperatures for either tape or substrate before the bonding of the tape onto the substrate at the nip line. One of the potential solutions to minimize the temperature variation at the nip line is the optimization of the laser location, orientation and/or laser distribution with respect to different winding/placement angles and different geometrical configurations. This is part of currently ongoing work.

Chapter 6

Process optimization framework for controlling the unsteady bonding temperature

¹ This paper presents an effective process optimization methodology for laser assisted tape winding (LATW) of complex part geometries by means of a numerical optical-thermal model. A winding path on the cylindrical and ellipsoidal (dome) part of a pressure vessel is considered with varying tooling curvature. First, the process model output is verified with the literature data based on the laser intensity distribution. Then, the transient laser irradiation and temperature distributions on the tape and substrate are described comprehensively. It is shown that the maximum laser intensity increases approximately by 80% and the process (bonding) temperature changes by 80C at the intersection of the cylindrical and dome section of the pressure vessel. In order to keep the transient process temperature constant, a robust optimization scheme is utilized by means of a genetic algorithm. The design variable is determined as the total laser power and temperature constraints are defined. The proposed optimization methodology regulates the temperature within 1.5C variation with respect to the desired value. In order to compensate the transient local curvature effects on the process temperature, the total laser power varies approximately between 30% and 175% of the reference (non-optimized) case.

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6.1 Introduction

Laser assisted tape winding (LATW) and placement (LATP) are automated manufacturing techniques to produce high performance fiber reinforced thermoplastic (FRTTP) composite parts. Some examples for composite products manufactured by the LATW process are pipes in oil and gas industry [65, 112, 61], low cost type-IV pressure vessels as storage tanks in the transportation sector [113] or over-wrapped pressure vessels for fuel tank applications in the aerospace industry [114, 115]. The incoming thermoplastic composite prepreg tape and already wound substrate or tooling are heated using a laser source and bonded under the application of a pressure exerted by a compaction roller in LATW processes [26]. An in-situ consolidation of the FRTTP wound layers makes the LATW process advantageous and faster as compared with the conventional filament winding process using thermoset composites. The bonding temperature of the deposited layers plays a critical role for the process induced residual stresses [116, 107, 110] as well as the product quality and performance of the wound or placed FRTTP parts, e.g. the interlaminar bond strength of the deposited layers [6, 104] and the interlaminar void content [28]. The control of the bonding temperature is a difficult task especially during deposition of composite layers on a curved surface with curvilinear fiber paths such as the cylindrical and dome parts of pressure vessels. Due to the change in the local curvature during winding or placing FRTTP tapes on complex geometries, e.g. dome part of a pressure vessel, the process temperature changes and an unsteady thermal history is present [117]. In addition, the process temperature is also influenced by the winding angle due to the change in the local geometry as shown in [34]. Therefore, comprehensive temperature control approaches are needed to minimize the temperature variation and keep the process temperature within the desired target temperature boundaries.

The majority of studies to date in the literature focused on describing and predicting the temperature evolution during the LATP and LATW processes of FRTTP composites. Thermal models were developed in [118, 11–14, 16, 15, 17, 109, 94] for LATP on flat tooling by assuming a uniform heat flux distributed on the substrate and tape. In order to define a more realistic heat flux distribution, the reflection and absorption of the laser irradiation were modeled by using an optical process model in [33, 7, 12, 68, 6] for the LATP process with flat tooling geometries and in [39, 72, 119, 82, 30, 92, 83, 91, 34] for the LATW process with cylindrical shaped tooling. It was shown by using these optical models that there was a shadow region without any heat flux prior to the nip point at which the incoming FRTTP prepreg tape and already deposited layer were bonded. This resulted in a temperature drop near the non-irradiated nip point.

The numerical thermal process models were coupled with crystallization models in [16, 15, 120] to predict the final bonding quality and material properties of the FRTTP

composites produced by automated tape placement or winding processes. The optimum process temperature and its range were obtained based on the fracture toughness [19], the interlaminar peel resistance [20], the wedge peel strength [27] and the product quality [21] of the FRTP parts manufactured by automated tape placement processes. Although the importance of the process temperature has been recognized in literature, there has been limited research that has addressed the process optimization for obtaining the optimum temperature range and distribution. Recently, an inverse thermal model was developed in [22] to achieve the required heat flux distributions for a given desired heating profile on a flat tooling geometry. In [121], the optimum laser power distribution was obtained based on the desired temperature distribution by means of an inverse optical model coupled with an inverse thermal model. The obtained laser power distribution can be realized by using a vertical-cavity surface-emitting laser (VSCEL) as proposed in [67, 117] by modifying the optical inputs of each emitter in the VSCEL.

Despite the large amounts of researches for modeling and optimization of the LATW and LATP processes in the literature, there has been no generic approach for complex curved surfaces such as the dome parts of pressure vessels to simulate and control the transient temperature behavior. The aim of the present work is to optimize the LATW process with complex tooling geometries on which the laser irradiation and temperature profiles change as a function of time. To this end, a new optimization framework is developed by means of a genetic algorithm (GA). The objective is to keep the process temperature within the desired temperature limits during winding of FRTP tapes onto complex curved surfaces. In this work the emphasis is on the winding of FRTP tapes on the cylindrical and dome parts of a pressure vessel. A three-dimensional (3D) optical-thermal process model is developed for the prediction of the transient laser power intensity and the temperature distribution near the nip point on curved surfaces. The ray-tracing optical technique is employed to supply the heat flux for the advection-diffusion thermal model. Based on the developed physics-based model, a transient process optimization on each incremental movement (kinematics) is performed to find the optimum laser power at each time step to minimize any variation in the desired process temperature.

The following section describes the problem description for the pressure vessel winding. Section 3 presents the coupled optical-thermal process model of the LATW process. Subsequently, the novel optimization framework is described in Section 4, after which the results are discussed in Section 5. Finally, the conclusions and recommendations for future work are presented in Section 6.

6.2 Problem description

In order to study the effect of unsteady curvature change during the LATW or LATP processes, a sufficiently generic example was considered to clearly describe the emerging optical-thermal phenomena during LATW processes. The winding path of the current example for winding a carbon fiber reinforced PA6 (C/PA6) prepreg tape on an already wound substrate on the pressure vessel is schematically shown in Figure 6.1a. The fiber volume content (FVC) of C/PA6 tape was 48% which was taken from [64]. The total winding path distance considered in the present work was $d = 313.6$ mm and the linear winding velocity (v) was set to 50 mm/s. A total of 161 time steps (ts) were defined for the winding kinematics in which a length of $\Delta d = 1.95$ mm tape was deposited on the substrate with a time increment of $\Delta t = 39$ ms. The winding path was in parallel to the axial direction of the pressure vessel on the cylindrical part. The location of the roller, the incoming tape and the laser irradiation are schematically shown in Figure 6.1b. The winding path began at $ts = 1$ on the cylindrical part of the pressure vessel and continued on the dome part following a geodesic path until $ts = 161$. The intersection of the cylindrical and dome part of the pressure vessel took place at $ts = 77$ as seen in Figure 6.1b. The position of the laser source with respect to the roller/tape orientation remained the same as reported also in [117, 26]. However, the relative orientation of laser source toward the tooling/substrate continuously changed due to the surface curvature of the dome part. The corresponding laser angle (θ) and normalized tooling surface curvature evolution as a function of ts for the nip point location are given in Figure 6.2. As a result of changing curvature and laser angle, the incident angle of the laser rays on the substrate/tooling and the angle of reflected rays from the substrate/tooling surface varied on the dome part, i.e. from $ts = 77$ to $ts = 161$ and they remained the same from $ts = 1$ to $ts = 77$ on the cylindrical part. However, the influence of the changes in curvature from the cylindrical to the dome section of the pressure vessel became evident much earlier than when the nip point location arrived at the dome section. In fact as soon as the laser irradiated area on the tooling included a portion of the dome section a considerable local heating of that part of the dome took place as explained further in the following.

An illustration of the change in incident angles of the laser rays on the pressure vessel and the laser reflections from substrate/tooling and tape/roller for different locations (d) and time steps (ts) of the consolidation roller is given in Figure 6.3. The pictures in this figure show the geometry of the incident laser rays (green color) and the reflected rays from the tape/roller (blue color) and the substrate/tooling (red color). From $d = 0$ to approximately $d = 93.5$ mm ($ts = 48$), the laser only irradiated the cylindrical part. At the beginning of the dome irradiation, the laser incident angles increased and reflection directions from the tooling changed as shown at $d = 107.1$ mm ($ts = 55$). The incident angles on the dome part

became more perpendicular where a smaller region on the cylindrical part was irradiated as seen on $d = 136.4$ mm ($ts = 70$). As the geometry of the irradiated dome was not constant, further movement on the winding path caused different incident angles throughout the tooling surface as seen on $d = 150$ mm ($ts = 77$). At $d = 150$ mm, the roller was at the intersection of cylinder-dome after which further movement on the winding path caused rotation of the laser/tape/roller system. Note that the laser source was oriented with respect to the tape feeding system. Hence, the orientation of the laser rays and tape/roller reflections toward the tooling/substrate changed as seen on $d = 155.9$ mm ($ts = 80$). Further movement on the dome, e.g. at $d = 165.6$ mm ($ts = 85$) and $d = 313.6$ mm ($ts = 161$), did not significantly change the laser rays or reflections as the curvature of the winding path only slightly changed in the remainder of the path as seen in Figure 6.2. Thus, the most critical location in Figure 6.3 was at the transition region from the cylindrical to the dome part of the tooling due to the significant change in the tooling/substrate curvature.

The winding process defined in Figure 6.1 for the cylindrical and dome parts of the pressure vessel was numerically simulated in order to predict the laser intensity and temperature distributions in the tape and the substrate and allow subsequent process optimization of the LATW process. The details of the optical-thermal process model are explained in the following section.

Fig. 6.1 Schematic view of the winding path (a) and kinematics (b) on the pressure vessel for different locations. Note the variation in the laser orientation (angle theta) along the winding path from the start (first time step (ts)) to the finish of the winding path ($ts = 161$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

6.3 Numerical process simulation tool

A generic combined optical-thermal simulation tool was developed based on the work reported in [34] for LATP and LATW processes. This numerical process model was part

Fig. 6.2 The evolution of the laser angle (θ) and normalized tooling curvature at the nip point location as a function of the time step (ts). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Fig. 6.3 A schematic view of the incoming laser rays (green), the reflected laser rays from tape or roller (blue) and the reflected rays from tooling or already wound substrate (red) at different locations on the pressure vessel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

of a more comprehensive software named OTOM (Optimizing Thermal Optical Model) developed at the University of Twente by using MATLAB.

The flowchart of the developed transient optical-thermal process model is represented in Figure 6.4. First the geometrical and process data were collected and the kinematics were then updated by moving the roller over a small distance on the winding path (see Figure 6.1).

Fig. 6.4 The flowchart of the transient coupled optical-thermal process simulation model.

Next, the optical model based on a ray tracing approach was employed to provide the heat flux to the thermal model. The boundary and initial conditions (BCs & ICs) in the thermal model were then updated and the temperature distributions in the tape and the substrate were calculated at the current time step ts corresponding to a specific location on the winding path. The procedure was carried out until the end of the winding path described in section 6.2. The details of the optical and thermal models are explained in the following sections.

6.3.1 Optical model

A parametric 3D optical model with the ray-tracing approach was developed based on the generic model created in [34]. A schematic view of the model geometry is given in Figure 6.5a. A global coordinate system denoted as X , Y and Z was used in the optical model. Here, W_R and R_R were the roller width and radius, respectively, W_L and H_L were the width and height of the laser source defined as a plane toward the nip line N_1 - N_2 , respectively. The contact region between the tape and roller was defined with the angle θ_R . The tape and substrate width were considered as W_T and W_S , respectively. A 3D ray tracing approach was employed as seen schematically in Figure 6.5b. The position of the laser source including the location $P_L(X, Y, Z)$ and orientation θ_L , were defined with respect to the nip line N_1 - N_2 . The details of the optical model and its implementation can be found in [34]. The geometrical parameters used in the optical analysis are summarized in Table 6.1.

A uniform laser power distribution with a magnitude of $P_{laser} = 430$ W without a divergence angle was modeled. The incoming rays were assumed to reflect specularly here based on previously validated model of current authors in [34, 119] to capture main trends of physical phenomena with less computational time comparing to the anisotropic reflection modeling. Only one reflection was considered in the optical model as in [33] to save computational cost, because the energy carried by the second and following reflected rays was less than 5% of the energy of the incoming ray [39]. The refractive indices of the composite prepreg and

deformable roller were taken from [36] with a value of 1.95 and 1.43, respectively. A total of 10200 laser rays were utilized in the optical model with 120 rays along the width and 85 rays along the height of the laser source plane.

As aforementioned in Section 6.2, the laser irradiation and reflection on the substrate and tape at every time step (ts) were modelled based on the local surface curvature and laser orientation. The discretization of the winding path is illustrated in Figure 6.6 for two different times steps and substrate configurations (region of interest for the optical-thermal model). It is seen that the substrate domain followed the winding path and moved incrementally with a distance of Δd which was determined based on the time increment (Δt) and linear winding speed (v). Although the tape geometry did not change during the winding process, the laser reflections from the substrate and tooling surfaces affected the total laser power acting on the tape. The output of the optical model was the laser intensity distribution on the incoming tape and substrate surface as a function of time coupled with the local tooling curvature.

Fig. 6.5 (a) Geometry of the parametric 3D optical model. (b) Schematic of ray-tracing approach with incoming ray and reflections from substrate and tape with respect to the surface normals. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

6.3.2 Thermal model

The tape and substrate geometry defined in Figure 6.5 were unfolded into a flat Cartesian coordinate system to calculate the temperature distributions in the tape and the substrate domains. The heat transfer modeling of tape and substrate here was considered just before the nip point (before coming into contact). A local coordinate system denoted as x , y and z was employed in the thermal models for the tape and substrate domains. The thickness of the tape is usually very thin as compared to the one of the substrate which plays a role to acquire a uniform temperature distribution in the through-thickness direction for the tape and

Table 6.1 Geometrical parameters used in the current modeling work according to the schematic geometrical model domain given in Figure 6.5.

Geometrical parameters	Symbol	Value	Unit
Relative laser location (X,Y) w.r.t nip	P_L	110, 43	[mm]
Laser source width	W_L	20	[mm]
Laser source height	W_H	30	[mm]
Laser source angle	θ_L	22.6	[]
Tape width	W_T	12.5 [73]	[mm]
Tape thickness	th_T	0.25 [73]	[mm]
Roller radius	R_R	45	[mm]
Roller width	W_R	50	[mm]
Length of flat part of tape	$L_{T,flat}$	78	[mm]
Tape-roller contact angle	θ_R	60.0	[]
Substrate length	L_S	60	[mm]
Substrate width	W_S	12.5	[mm]
Substrate thickness	th_S	0.60	[mm]
tooling radius	R_M	100	[mm]
Ellipsoidal dome semi axis in Z-direction	c_D	25	[mm]

Fig. 6.6 Schematic view of the winding path and two different substrate domains situated at different time steps with different curvature. At each time step (ts), the roller, tape and substrate domains followed the discretized winding path with a distance of Δd as indicated with black circles. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article).

non-uniform one for the thicker substrate. Therefore, 2D and 3D heat conduction models were considered for the tape and substrate, respectively, as employed in [34, 119]. The thermal computational domains for tape (2D) and substrate (3D) are depicted in Figure 6.7. The geometrical parameters can be found in Table 6.1. The governing equations used for the tape and substrate domains are given as [34]:

$$\rho C_p \left(\frac{\partial T}{\partial t} + v \frac{\partial T}{\partial x} \right) = k_x \left(\frac{\partial^2 T}{\partial x^2} \right) + k_y \left(\frac{\partial^2 T}{\partial y^2} \right), \quad \text{Tape} \quad (6.1)$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + v \frac{\partial T}{\partial x} \right) = k_x \left(\frac{\partial^2 T}{\partial x^2} \right) + k_y \left(\frac{\partial^2 T}{\partial y^2} \right) + k_z \left(\frac{\partial^2 T}{\partial z^2} \right), \quad \text{Substrate} \quad (6.2)$$

where t was the time, T was the temperature, v was the linear winding velocity showing the material movement toward the nip line, C_p was the specific heat, ρ was the density, x , y and z represented the local spatial locations, k_x , k_y and k_z were the coefficients of thermal conductivity of the composite material in x -, y -, z -direction, respectively.

The heat flux distributions obtained from the optical analysis were provided to the tape surface and the top surface of the substrate at $z = 0$, see Figure 6.7. Next to the heat flux boundary condition, a convective heat transfer was defined on these surfaces with the ambient air temperature (T_{air}) by assigning a convective heat transfer coefficient (CHTC) h_{air} . Similarly, a CHTC was used for the tape-roller interface (h_R with the roller temperature T_{roller}) for $(L_T - L_{T,flat} < x < L_T)$ and the substrate-tooling interface ($h_{tooling}$ with the tooling temperature $T_{tooling}$) at $z = th_S$. It should be noted that although the heat conduction was defined in 2D for the tape, the heat convection boundary conditions were utilized in the direction normal to the tape surface (i.e. at the tape-roller and tape-air interface) as described in [34, 119]. An adiabatic boundary condition was modeled for the remaining boundaries for tape and substrate domains including the nip line. The temperature distribution from the previous time step ($ts - 1$) was considered as the initial condition of the tape and substrate thermal domains in the current time step (ts). At $ts = 1$, the initial temperature was set to T_{air} (see [34, 119] for more elaboration on implementing boundary conditions).

A control volume based finite difference technique with upwind implicit scheme as used in [96, 97] was employed in the present work to solve the governing equations with the defined boundary conditions. The advection term ($v \frac{\partial T}{\partial x}$) in the heat transfer equation was implemented using a Eulerian frame work. A structured control volume based mesh was therefore defined in the respective local coordinate systems of the tape and substrate domains. The total number of control volumes was determined as 450 (30 and 15 in the x - and y -direction, respectively) for the tape and 2250 (30, 15 and 5 in the x -, y - and z -direction, respectively) for the substrate based on initial convergence studies. The values used for the thermal properties and boundary conditions are listed in Table 6.2 which were determined based on the available data in literature [64].

Fig. 6.7 Schematic view of the thermal domains for tape and substrate which were unfolded from the optical domain defined in Figure 6.5.

Table 6.2 Process and material variables used in the current modeling work.

Process/material parameters	Symbol	Value	Unit
Composite thermal conductivity	k_x, k_y, k_z	5.0, 0.45, 0.45 [64]	[W/(m-K)]
Composite density	ρ	1450 [64]	[kg/m ³]
Composite specific heat	C_p	1600 [64]	[J/(kg-K)]
Air heat transfer coefficient	h_{air}	10 [6]	[W/(m ² -K)]
Air temperature	T_{air}	20	[°C]
Roller heat transfer coefficient	h_R	100 [6]	[W/(m ² -K)]
Roller temperature	T_{roller}	20	[°C]
Tooling heat transfer coefficient	$h_{tooling}$	100 [6]	[W/(m ² -K)]
Tooling temperature	$T_{tooling}$	20	[°C]
Incoming material temperature	$T_{incoming}$	20	[°C]

6.4 Numerical Process optimization

Local changes in the tooling curvature affect the distribution of absorbed and reflected laser light and may cause strong local variations in the temperature distributions of the tape and substrate domains even at constant laser power and linear winding speed as mentioned in section 6.2. Therefore, the main objective of the process optimization was to keep the nip point temperature constant at the desired temperature value ($T_{desired}$) for each time step (ts) on the winding path. The nip point temperature (T_{nip}) was defined as the mean of the average substrate temperature (T_{nip}^S) and tape temperature (T_{nip}^T) along the nip line as N₁-N₂ seen in Figure 6.5, i.e. $T_{nip} = (T_{nip}^S + T_{nip}^T)/2$ by assuming the heat capacities of the tape and substrate were comparable. The nip point temperature was defined in a similar way in [19, 41] because the tape and substrate temperatures at the nip point were defined at the surface and therefore there is no time for heat to be transferred at the tape-substrate interface. The design variable of the optimization problem was defined as the total laser power (P). Note that the uniform nature of the laser power distribution remained unchanged. The optimization constraints were defined as the maximum and minimum allowable temperature as T_{upper} and T_{lower} , respectively, for the nip point temperatures of both domains T_{nip}^S and T_{nip}^T .

In this single objective problem (SOP), any change in P may not be reflected directly on T_{nip} at the same time step (ts). The reason is related to the shadow region near the nip point at which the heat flux or the laser irradiation is zero because the laser rays cannot reach the nip point as described also in [36, 34]. An illustration of a typical heat flux and temperature distribution including the shadow region in the LATW and LATP processes is depicted in Figure 6.8 [36, 34]. The time required for a material point to pass the shadow length is expressed as the shadow length duration, ts_{shadow} . Since the material point moved along the discretized thermal points on the winding path (see Figure 6.6), the stepwise ts_{shadow} was

considered in the optimization problem. It should be noted that ts_{shadow} for the substrate was affected by the tooling curvature. It is seen that the maximum temperature occurs just prior to the shadow region due to the advection of the material with the linear winding speed. The maximum temperature is therefore advected towards the nip point which results in an increase in T_{nip} at later stages in time. In other words, although the laser power is regulated at time step ts , its effect on T_{nip} is seen at $ts + ts_{shadow}$ as shown in Figure 6.8 due to the material advection. Hence, the optimization problem was constructed based on the design variable P at ts , i.e. $P(ts)$ and the output variable T_{nip} at $ts + ts_{shadow}$, i.e. $T_{nip}(ts + ts_{shadow})$. The corresponding SOP was formulated as:

$$\begin{aligned} \text{Minimize : } f_1(P(ts)) &= |T_{nip}(ts + ts_{shadow}) - T_{desired}| \\ \text{subject to : } g_1(P(ts)) &= T_{lower} < T_{nip}^S(ts + ts_{shadow}) < T_{upper} \\ g_2(P(ts)) &= T_{lower} < T_{nip}^T(ts + ts_{shadow}) < T_{upper} \end{aligned} \quad (6.3)$$

where T_{upper} and T_{lower} were the upper and lower temperature constraints, respectively for T_{nip}^S and T_{nip}^T . The process optimization problem defined in Equation 6.3 was a single objective problem where a change in either tape or substrate temperature influences other components (tape or substrate) to compensate for the temperature change. This caused opposite behavior of the tape and substrate temperatures during the optimization procedure. In the present process optimization case, the values of $T_{desired}$, T_{upper} and T_{lower} were set to 270 °C, 380 °C and 220 °C, respectively, based on the experimental work done in [27] for the LATP process of C/PA6 composites. Here, $T_{desired}$ was considered as the optimum process temperature that gave the highest wedge peel strength of the C/PA6 laminates, T_{upper} was the degradation temperature and T_{lower} was defined as the melting temperature according to [27]. It should be noted that the current optimization program did not include the overheating in the region prior to the nip point (prior to the shadow region) to avoid more complexity.

The optimization procedure explained in this section is summarized by using a flowchart seen in Figure 6.9. The SOP defined in Equation 6.3 was solved by employing a GA developed in MATLAB. A population size of 90, 4.5% elitism, two-point crossover with crossover fraction of 0.8 and 5% probability of uniform mutation were applied in the GA. The details of these common genetic operators can be found in [122]. The tolerance for the objective function evaluation was set to 0.01 °C in MATLAB in order to have a sufficient accuracy in the optimization algorithm, i.e. when $f_1 \leq 0.01$ the iteration loop in GA was stopped. The GA procedure was repeated 10 times to obtain the global optimum and the best solution was considered in the present work.

Fig. 6.8 Typical heat flux and temperature distributions for the substrate in LATP and LATW processes and the illustration of the shadow region prior to the nip point. Here, t_{shadow} is the time required for a material point to pass the shadow length.

6.5 Results and discussions

6.5.1 Reference case

In this section, the process simulation results for the pressure vessel winding defined in Figure 6.1 are presented. The total laser power remained constant ($P = 430$ W) at each location of the winding path. The absorbed laser intensity and temperature distributions on the tape and substrate were obtained from the optical-thermal model. The predicted laser intensity distribution on the cylindrical part of the pressure vessel was verified by comparing it with the optical model developed in [30]. The laser intensity distributions at the centerline of the tape and substrate predicted by the current numerical optical model with the OTOM simulation tool and by the numerical and analytical models developed in [30] for flat surfaces are shown in Figure 6.10. It is seen that similar trends of laser intensity distributions were obtained between the current model and the available models in literature both for the tape and the substrate. The scatter in the laser intensity distribution visible in both numerical models was related to the nature of the discretization of the surface and the limited total number of rays employed which did not deteriorate the validity of the results for the temperature analysis [34, 119]. The laser intensity for the tape was the highest ($4.5\text{--}5 \times 10^5$ W/m²) at around 60 mm before the nip point and decreased to 0 at around 6–10 mm before the nip point which represented the shadow region as visible in Figure 6.10a. The laser reflections coming from the substrate on the tape surface are visible at the location

Fig. 6.9 Flowchart of the developed process optimization procedure.

Fig. 6.10 The absorbed laser intensity distributions at the centerline of a) tape and b) substrate on the cylindrical part of the pressure vessel, i.e. $ts = 1$ to 48 and the corresponding results obtained from the numerical and analytical optical models developed in [30] for flat surfaces. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

approximately 6–25 mm prior to the nip point. The maximum laser intensity of the substrate was lower than the tape due to the orientation of the laser source as shown in Figure 6.10b. The contribution of the laser reflections coming from the tape was visible on the substrate at the location approximately 40–48 mm from the nip point. The obtained laser intensity distributions and the locations of the reflections for the tape and substrate matched also quite well the observations reported in [123].

The absorbed laser intensity distributions on the surface of the tape and substrate predicted at different locations of the pressure vessel are shown in Figure 6.11. From $ts = 1$ to $ts = 48$ corresponding to $d = 0 - 93.5$ mm, the laser intensity distributions remained the same as the substrate in the optical model was completely on the cylindrical part. Most of the substrate surface was uniformly irradiated with intensity of around $3.5\text{--}4 \times 10^5$ W/m². A portion of

the substrate domain was situated on the dome part starting from $ts = 49$, i.e. the dome was irradiated where its surface had a larger surface gradient, and hence localized laser intensity was obtained on the substrate. At the same time, the laser intensity for the tape decreased due to a lower amount of reflections coming from the substrate. The localized intensity distributions for the substrate on the dome part are shown in Figure 6.11 for $ts = 55$ and 70. The intensification of the laser radiation on a smaller surface area of the substrate continued until $ts = 77$ or $d = 150$ mm where the substrate irradiation area was the smallest among all the time steps with the highest intensity value of approximately 8×10^5 W/m². The total irradiated area for the tape decreased from $ts = 49$ to $ts = 77$ due to the reduction in the reflections coming from the substrate. After $ts = 77$, the laser head was rotated strongly for the roller to follow the winding path on the dome section. The orientation of the laser head with respect to the substrate returned to nearly the same orientation as for the cylindrical section of the pressure vessel as can be seen from Figure 6.3. Thus, the localization/intensification of the laser intensity on the substrate domain started decreasing after $ts = 77$ as seen in Figure 6.11 and diminished almost completely at $ts = 90$. The tooling curvature also influenced the substrate shadow length prior to the nip point as seen in Figure 6.12. The shadow length decreased to 1.95 mm for $ts = 77 - 79$ where the highest tooling curvature took place as seen in Figure 6.2. The obtained results in Figure 6.11 were in accordance with the findings in [124] where the intensity change was observed during winding on a rounded corner edge.

To analyze the laser power intensity on the substrate and tape surfaces in a more detailed way, the evolution of the total power and normalized maximum power intensity and their relations with the substrate/tooling curvature were investigated as depicted in Figure 6.13. Three exemplary locations on the substrate including the inlet ($A_1 - A_2$ in Figure 6.6), the nip point ($N_1 - N_2$ in Figure 6.6), and middle of them (between inlet and nip point along the winding path) were selected to illustrate the evolution of local curvature. The maximum intensities of the tape and substrate were normalized by their corresponding maximum value on the cylindrical part, $ts = 1 - 48$. Overall, the magnitude of the absorbed power by the substrate and tape was approximately 155 W and 105 W, respectively, for $ts = 1 - 48$. The rest of total power was absorbed by the tooling and the roller, and some portion was reflected toward the ambient. The following observations were obtained from Figure 6.13:

- From P1 to P2 ($ts = 49 - 58$): The incident angles on the substrate surface gradually increased (the inlet location) and the irradiated area was decreased. Hence, the absorbed power for substrate increased. On the other hand, the power absorbed by the tape decreased due to the reduction in laser reflections from the tooling and substrate surface. Overall, the absorbed laser intensity for the substrate increased significantly from P1 to

Fig. 6.11 Absorbed power intensity distributions for the tape and substrate at different locations on the winding path defined for the pressure vessel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Fig. 6.12 Evolution of the shadow length at the centerline of the substrate. Note that the shadow length was derived from the intensity distribution on the discretized substrate domain.

P2 due to the change in the local substrate curvature and increasing angles of incidence on the substrate. The variation in normalized maximum intensity for the tape was less than 0.03 and related to the change in reflections coming from the substrate.

- From P2 to P3 ($ts = 58 - 77$): The incident angles on the substrate further increased due to the increase in substrate curvature especially at locations before the nip point as seen in Figure 6.13c). The normalized substrate intensity had its maximum which was approximately 1.8 at $ts = 77$, i.e. at the cylinder-dome intersection, which was found to agree well with the findings in [124].
- From P3 to P4 ($ts = 77 - 88$): The incident angles on the substrate gradually decreased and the size of the irradiated substrate area increased due to the decrease in the substrate curvature on locations before the nip point as seen in Figure 6.11. Although the substrate curvature on the nip point started increasing at P3, this increase did not affect the substrate normalized intensity as the nip point location was in the shadow region and the incident angles were relatively low at the shadow region. The normalized maximum intensity for the substrate decreased to a value of approximately 1.2. The absorbed power for the substrate first increased until $ts = 81$ due to a stronger contribution of reflections from the tape and the roller, then decreased after $ts = 81$ due to the decrease in the substrate curvature. On the other hand, the absorbed power for the tape increased due to the increase in the contribution of the reflected rays from the substrate/tooling.
- From P4 to P5 ($ts = 88 - 144$): The substrate normalized curvatures were relatively small, however larger than the curvature on the cylindrical part ($ts = 1 - 48$). Therefore, an approximately 20 % increase in the normalized maximum intensity for the substrate occurred as compared with the cylindrical section of the pressure vessel.
- From P5 to the end ($ts = 144 - 161$): The laser irradiated the curved lower part of the dome section of the pressure vessel where the substrate normalized curvature of the inlet location increased. As a result, the localized behavior of the absorbed laser radiation occurred again leading to higher normalized maximum intensity values of the substrate.

The 2D tape and 3D substrate temperature distributions for different locations on the pressure vessel are shown in Figure 6.14. The localized intensity near the inlet of the substrate domain caused a relatively small increase in the substrate temperature at $ts = 55$. This is elaborated more in the following sections. The changes in the substrate temperature distribution became more significant once the intensification of the absorbed laser intensity

Fig. 6.13 Evolution of a) the total absorbed power and b) normalized maximum intensity together with c) the substrate normalized curvature at different locations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

further increased between $ts = 70$ and $ts = 77$ as clearly illustrated in Figure 6.14. It is seen that the maximum temperature rose up to approximately 460 C. Although the maximum intensity took place at $ts = 77$ as shown in Figure 6.13, the maximum temperature at the nip line occurred at a later stage in time, i.e. at $ts = 80$, due to the advection of the material during winding. After $ts = 80$, the substrate temperature at the nip line gradually decreased as illustrated for $ts = 85$ and $ts = 110$. The substrate temperature gradient at the nip point along the thickness was observed for the defined winding path in Figure 6.14 which was approximately between 80C-100 C. The variation in tape temperature distribution due to the change in reflections coming from tooling/substrate was much smaller than the variation in the substrate temperature in Figure 6.13. The behavior of tape and substrate temperatures can be more elaborated via their temperature profiles in the following. The spatial variation in the tape temperature per time step seemed more or less constant from the beginning until the end of the winding path as visible from Figure 6.14 by comparing the tape temperature

Fig. 6.14 Contour plots of the temperature distribution for the substrate and tape at different locations (time steps) on the pressure vessel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

distributions from $ts = 48$ to $ts = 80$. Similar evidence is visible from Figure 6.13b where the maximum normalized intensity of the tape remained constant at a value of 1. Hence, the occurring maximum in the absorbed intensity was hardly influenced by the followed winding path. This seems rather logical from the fixed orientation of the laser to the tape (see also Figure 6.1), but it also suggests that the contribution of the reflected rays from the substrate was either negligibly small or remained homogeneously distributed over the tape surface independent of the location on the winding path.

The transient evolutions of T_{nip} , T_{nip}^S and T_{nip}^T are shown in Figure 6.15 together with the centerline temperature distributions for substrate and tape at specific time steps. The centerline coincides with the x coordinate axes of the respective domains in Figure 6.7. It is seen that T_{nip} , T_{nip}^S and T_{nip}^T reached steady state temperatures of approximately 270 °C, 250 °C and 290 °C, respectively, with less than 2C variation at $ts = 40$ and these temperatures remained constant until about $ts = 65$. The temperature trends were found to be very similar

to the experimental measurements with constant velocity in [117] where the variation in temperature took place at the curved locations. The localization of the laser power intensity resulted in a local temperature increase in the substrate thermal domain as soon as a portion of the dome section was irradiated which can be seen from the temperature distribution at $ts = 55$ in Figure 6.15. The increased amount of heat accumulated due to tooling curvature as explained above and advected towards the nip point led to a significant temperature increase as can be seen clearly in the temperature distribution plots at $ts = 70$ and $ts = 77$. It also caused T_{nip} and T_{nip}^S to reach maximum values of approximately 350 °C and 460 °C, respectively at $ts = 80$. The tape temperature started decreasing from $ts = 61$ until $ts = 83$ due to the less reflections coming from the tooling/substrate. The minimum T_{nip}^T was calculated as approximately 250 °C at $ts = 83$.

The substrate temperature decreased gradually after $ts = 80$ as the localized intensity was gradually disappeared due to the decrease in the local tooling curvature change. It is seen from the temperature distribution plots in Figure 6.15 that there was a less steep increase in the centerline substrate temperature at $ts = 110$ than at $ts = 85$. As the localized heating disappeared for the substrate after $ts = 110$ since the irradiated area of the dome section was relatively flat, T_{nip} , T_{nip}^S and T_{nip}^T reached again a temperature plateau of approximately 275 °C. However, the reached plateau temperatures are somewhat higher than obtained for the cylindrical part (between $ts = 1$ and $ts = 48$) because of the slight curvature of the dome section between $ts = 110$ and $ts = 161$.

6.5.2 Optimization case

The development of the tape and substrate temperatures along the winding path from the beginning at the cylindrical section of the pressure vessel to the end at the dome section clearly showed the influence of the occurring changes in local curvature and orientation of the substrate surface with respect to the laser rays. A strong peak in the temperature occurred mainly at the transition from the cylindrical to the dome section. Hence, the optimization approach should limit the total amount of supplied laser power upon approaching the transition and adjust it precisely over the winding path to maintain the nip point temperature close enough to the desired value to remain within the provided bounds. The variation in T_{nip} presented in Figure 6.15 was minimized with respect to $T_{desired}$ by solving the SOP defined in Equation 6.3. The best and average fitness values as a function of the generation number for three exemplary time steps (corresponding to locations on pressure vessel) are shown in Figure 6.16. It is seen that the best and mean fitness values were gradually decreased until the generation around 50 where the best fitness was below the fitness function tolerance (0.01 C). Thus, the solution of the SOP was found to be converged. Although the convergence rate

Fig. 6.15 Evolution of T_{nip} , T_{nip}^S and T_{nip}^T as a function of ts . The centerline temperature distributions for substrate and tape at $ts = 48, 55, 70, 77, 80, 85$ and 110 . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

of each time step was not the same, the solution of the SOP was found to be converged for each location of the pressure vessel as described in Figure 6.9.

Fig. 6.16 Generations as a function of fitness values ($f_1(ts) = |T_{nip}(ts + ts_{shadow}) - T_{desired}|$) for best individuals and their average for several time steps.

The described optimization scheme in this paper searched for the optimum total laser power in each step to regulate T_{nip} as shown in Figure 6.17a. The tape and substrate absorbed powers and their corresponding normalized maximum intensities together with the substrate curvatures are also shown in Figure 6.17b and Figure 6.17c, respectively. It should be noted that the defined SOP was not employed for the cylindrical section, where the pressure vessel geometry and irradiation conditions remained constant, but commenced after $ts = 50$ where illumination of the dome section of the pressure vessel started. The same segmentation as in

Figure 6.13 was employed in Figure 6.17 to explain the obtained optimized transient power profiles. Although the maximum substrate intensity increased significantly from P1 to P2 due to the partial curvature of the substrate thermal domain at the inlet (see Figure 6.7), the optimized power remained roughly unchanged at 430 W. The influence of the local higher laser power input on the nip point became apparent only after $ts = 58$. Hence, a similar maximum intensity profile is obtained as for the non-optimized case described in Section 5.1. After P2 the optimized total power slightly increased by approximately 10 W at around $ts = 60$ as the tape temperature slightly decreased due to the reduction in the reflections coming from the substrate to the tape. When the substrate nip point temperature started increasing due to the presence of intensity localization at around $ts = 70$, the optimized total laser power decreased approximately by 125 W to compensate for this effect. As a result, the total absorbed power for substrate and tape and the normalized maximum intensity decreased as well. As soon as the roller came in contact with the dome, a large portion of the dome section was irradiated. However, some part of this portion was still at relatively low temperatures as it had not received much energy with using optimized low laser power which was approximately 125 W. Thus, the optimized power started increasing strongly at $ts = 77$ to compensate the lower heat input for that part of the dome which did not receive enough laser energy. The optimized power reached to approximately 750 W at $ts = 85$ where the corresponding total absorbed power and maximum normalized intensity of substrate and tape increased. After $ts = 85$, the optimized power approached to its nominal reference value of 430 W after the roller had arrived at the dome section of the pressure vessel and the laser head orientation became similar to that of the cylindrical section of the pressure vessel. It should be noted that the heat flux distributions on the substrate and tape domains in the winding direction were not uniform as seen in Figure 6.10. More specifically, the region farthest away from the nip point of the tape domain was heated the most due to the laser configuration. Therefore, any change in the total power resulted in a change in the nip point temperature at later stages which was inherently included in the optimization procedure. Therefore, the optimum total laser power after P4 varied slightly around 430 W in order to keep T_{nip} close to 270 C. The variation in the optimum total power profiles became smaller until the end of the winding path.

The evolution of the optimized T_{nip} , T_{nip}^S and T_{nip}^T together with the corresponding optimum laser power profiles and non-optimized T_{nip} , T_{nip}^S and T_{nip}^T are shown in Figure 6.18. The tape and substrate temperature distributions along the winding direction were carefully investigated for each ts and results from the selected time steps at $ts = 70, 77, 80, 85$ and 110 are exploited in Figure 6.18. It is seen that T_{nip} was maintained at the desired temperature of 270 C by regulating the total laser power at each ts . The modified laser power provided a

Fig. 6.17 Evolution of a) the optimized total power, absorbed power and b) normalized maximum intensity together with c) the normalized substrate curvature for different locations. The non-optimized total power and normalized maximum intensities for tape and substrate are shown as dash-dotted lines (for interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

maximum increase of approximately 1.5C for T_{nip} over the entire winding path according to the constraints set. At the beginning of the process optimization at around $ts = 50$, both T_{nip}^S and T_{nip}^T remained nearly steady. Afterward, T_{nip}^T gradually decreased approximately to 220 C and T_{nip}^S increased to 320 C. It is seen that T_{nip}^T was at the lower side of the allowable temperature which was defined as the constraint in the SOP. The adaptation of the optimized laser power successfully compensated the sharp increase in T_{nip} in the non-optimized case (see previous section) due to the tooling curvature at the beginning of the dome. The optimized substrate and tape temperature distributions at $ts = 70$ were found to be almost the same as those of the non-optimized case. The difference between the optimized and non-optimized temperature distributions became more significant at $ts = 77$ and $ts = 80$ after regulating the laser power. The maximum substrate temperature was found to decrease approximately 200 C as compared with the non-optimized case at $ts = 77$ and $ts = 80$. At $ts = 85$ and $ts = 110$, the optimized temperature distributions reached to the reference case

results once the roller followed the winding path on the dome section of the pressure vessel and the orientation of the laser rays to the substrate surface is similar to that of the cylindrical section of the pressure vessel.

The optimized average nip point temperature was found to be almost constant whereas the tape and substrate varied in an opposite way. Since the optimization goal was maintaining the average tape and substrate temperature at a constant value, the only way to achieve it was the opposite variation of them which was inherently fulfilled in the optimization algorithm. It is worth mentioning that the observed temperature difference between tape and substrate might cause different levels of the polymer squeeze-out-of-flow under the compaction roller [27], poor intimate contact and polymer interdiffusion which might affect the bonding quality. The variation in total laser power influenced not only the target temperature, but also the temperature distribution on the tape and substrate thermal domains. This can be seen in Figure 6.18 for the optimized and non-optimized cases at selected time steps. As a result, the location of time dependent minimum and maximum tape and substrate temperature at the nip point was changed as compared with the non-optimized case as seen in Figure 6.18.

The optimized solution seamlessly regulated the opposing tape and substrate behavior around the region with steep curvature changes to keep nip temperature constant as desired. It is also worth mentioning that achieving the regulated temperature profile at the critical regions (e.g. $ts = 80$) was not possible if the total laser power modifications at the previous steps were not carried out. The demonstrated of the non-optimized and optimized examples clearly showed that the temperature development of any point on the tape and the substrate is the result of the accumulation of heat over time at that point, i.e. of the local thermal history. Geometrical changes in the pressure vessel and local variations in the substrate curvature caused the local thermal history to be different from place to place. Hence, optimization of the magnitude of the laser power, as performed in this work, required the optimization approach to adjust the total laser power for each tape/substrate point well before that point reached the nip point to secure the desired nip point temperature is maintained. Any inaccurate power selection within one of the previous steps can deteriorate the results of the following steps.

The presented optimization approach enabled the nip point temperature to be maintained within set limits. The restrictions of the presented approach based on the magnitude of the laser power can be investigated by performing a larger set of cases. Also, further constraints can be set to the maximum temperature reached by the tape and/or substrate just before the nip point to prevent local overheating and deterioration of the material properties. Evidently, for more complex cases the relatively simple approach followed here which optimizes only the magnitude of the laser power may not be sufficient to maintain a constant nip point

temperature and other approaches allowing for the laser power distribution to be adapted need to be pursued albeit at the cost of a higher complexity.

Fig. 6.18 Evolution of the optimized T_{nip} , T_{nip}^S and T_{nip}^T as a function of ts (at the center). In addition the non-optimized, i.e. the reference case, for T_{nip} , T_{nip}^S , T_{nip}^T and the optimized total power evolution are shown. The centerline temperature distributions of substrate and tape for the optimized (solid lines) and non-optimized (dashed lines) at $ts = 70, 77, 80, 85$ and 110 are shown on the sides. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

6.6 Conclusions

A new optimization framework specific for the LATP/LATW processes on complex curved surfaces such as the dome part of a pressure vessel was presented. A transient optical-thermal process model was developed which was used in a single objective problem. The process model was verified by comparing the predicted laser power intensities and temperature distributions on the substrate and tape domains with the available data in literature. The influence of the surface curvature change on the absorbed intensity and process temperature during winding of C/PA6 prepreg tapes was first investigated along the defined winding path by keeping the total laser power constant at 430 W. The nip point temperature was

found to be approximately 80 C higher than the desired process temperature. This was due to the sharp curvature change at the transition region between the cylindrical and dome part of the pressure vessel. The maximum laser intensity at the substrate surface was found to increase approximately by 80% due to the local tooling curvature. To prevent temperature variations for reliable manufacturing, an optimization framework based on a genetic algorithm was proposed by taking the shadow region close to the nip point into account. The main optimization goal was to keep the nip point temperature at the desired temperature level which was subjected to allowable lower and upper temperature limits for the tape and substrate at the nip point. The total laser power was selected as the only design variable. The optimum laser power evolution with respect to the varying tooling geometry (transition between cylinder and dome) was obtained which kept the nip point temperature at 270 C with a maximum of 1.5 C variation. The total laser power was found to vary between 125 W and 750 W to compensate for the transient local curvature effects on the process temperature.

The proposed physics based process model and the process optimization can be applied to the LATW process of any kind of pressure vessel geometries. This would pave the road to have a better digitalization of fiber reinforced composite manufacturing, improved final product quality and minimized production time and cost for lightweight composites. The main limitation of the proposed optimization framework was the complexity of the design variables. The correlation between the tape and substrate opposing temperature behavior along the winding path was the key in the current example in order to maintain the nip temperature constant as the only input variable was the total laser power. In order to control not only the average nip point temperature but also the individual nip point temperatures of substrate and tape, limits to the laser power distribution and maximum temperature prior to nip point should be included in the design variables which are considered as a future work. Incorporating heat capacitance and other physical/geometrical parameters e.g. thickness or fiber volume fraction variation into the optimization goal are suggested as future works as well in full-scale analysis.

Chapter 7

Discussion

In this chapter, a comprehensive overview of the main results obtained in the previous chapters is provided. A broader view on each research objective defined in the first chapter is presented. Suggestions for further research are also given as a future outlook to achieve a robust laser assisted tape winding process of fiber reinforced thermoplastic composites.

7.1 General discussion

The overall objective of this Ph.D. thesis was to achieve a robust LATW process by compensating the variability in the manufacturing process, resulting in repetitive and predictable part properties and performance. The specific research objectives defined in Chapter 1 were:

- To characterize the optical parameters of prepreg tapes for accurate process modeling (Chapter 2)
- To quantify the sources of temperature variation during a continuous LATW process (Chapter 3)
- To accurately predict the process temperature evolution in adjacent hoop winding of pressure vessels (Chapter 4)
- To identify the effect of winding angle, vessel diameter, and tape thickness on the laser intensity and temperature distributions (Chapter 5)
- To optimize the LATW process with complex tooling geometries and variable curvatures (Chapter 6)

These objectives were addressed in the previous chapters. The generated results in this thesis provide essential steps towards a fast local process model to be employed for in-line

Fig. 7.1 The inputs and outputs of the developed process simulation tool OTOM.

process control. The multi-physics based local process modelling tool named OTOM (Optical Thermal Optimization Model) was one of the outputs of the study. OTOM includes a coupled optical and thermal model capable of predicting the temperature distribution during the LATW process of arbitrary geometries by considering the local surface curvature, the thermal conditions of the previously wound layers, the winding angles, the laser light distribution and the material properties of the tape and other relevant components. An overview of the input and output of the developed process simulation tool is shown in Figure 7.1.

Considering the schematic overview in Figure 7.1, the thermal properties and boundary conditions were taken from the literature in the presented chapters. The optical properties of the tapes used in LATW processes were characterized in Chapter 2 based on the reflectance and anisotropic reflection behavior at room temperature. Corresponding optical model parameters were determined based on the experimental observations which can be used as inputs for an accurate local process model. It was shown in [82] that similar tape and substrate temperature distributions were obtained by using the specular reflection and anisotropic reflection model for 0 fiber orientation of the substrate.

Therefore, for the sake of simplicity and computation speed, the specular reflection model was utilized in the OTOM simulations presented in this thesis in which the fiber orientation of the substrate was considered to be 0. Hence, the effect of different fiber orientations for the substrate on the temperature distributions still needs to be addressed by using the anisotropic reflection model. To further improve the accuracy, it is also required to characterize the temperature dependent optical and thermal properties of the tapes and employ these in future local process simulations.

The geometrical parameters need to be made available for the local process model. Several geometrical parameters were examined in this thesis: the substrate thickness and roller deformation in Chapter 4, the mandrel radius in Chapters 4 and 5, the tooling curvature in Chapter 6. It was shown that the substrate thickness has an effect on the accumulated heat in the substrate during continuous adjacent winding. Higher substrate temperatures were observed for the mandrel with a relatively small radius due to larger laser incident angles, leading to the absorption of more laser energy. The sharp tooling curvature change at the transition region between the cylindrical and dome part of the pressure vessel influenced the substrate temperature significantly. The maximum laser intensity on the substrate was found to increase approximately by 80% due to the local tooling curvature. In the preceding chapters, a relatively simple fiber layup was considered by assuming that each layer of the substrate was oriented in the tape deposition direction. This is one of the limitations in the current local process model. Therefore, a more realistic local fiber layup definition is needed to capture the effect of fiber orientation during the helical winding process. In addition, as shown in Chapter 3, there may be gaps and overlaps in the already wound layers due to the kinematics of the winding process leading to variations in the temperature distribution. These local geometrical effects can be included in the local process model, however, this would result in an unfavorable, computationally expensive model while it would require an unfeasibly fast response time of a control system to compensate for this, and the contribution to the overall heat accumulation may be very limited. Instead, the variations observed in the measured temperature in Chapter 3 due to the gaps and overlaps can be filtered out which would be a more effective way to avoid the disturbances arising from the inherent local geometrical changes.

Various process parameters were included explicitly in the local process modelling tool OTOM namely the winding angle and speed, the divergence angle of the laser source, the power distribution and the winding path. The local process model was applied to three winding patterns: continuous adjacent hoop winding in Chapter 4, helical winding in Chapter 5 and winding on the dome part of a pressure vessel in Chapter 6. The computational parameters such as the mesh size of the thermal domain, the grid size of the laser source, the number of laser rays and the time step were determined based on the sensitivity analysis in the process simulations. A comprehensive analysis was made of the laser intensity and temperature distributions on the tape and substrate.

A transient curvature-dependent optical-thermal process model was developed which was used in the single-objective problem where the provided time dependent laser power was optimized to keep the nip point temperature within a limited temperature range. An optimum laser power evolution was obtained with respect to the varying mandrel geometry (transition

between cylinder and dome). The developed optimization framework can in principle be applied to an arbitrary pressure vessel geometry and winding paths. The main limitation of the proposed optimization framework was the complexity of the design variables as in this thesis only the nip point temperature was taken into account. In order to also control the separate substrate and tape temperatures in the vicinity of the nip point, the laser power distribution can be included in the design variables. Thus, the capabilities of the recently developed vertical cavity surface emitting laser (VCSEL) technology, which allows the use of such a discrete laser power distribution, can be exploited in an optimized manner [67].

The developed multi-physics based local model paves the way towards a digitalized LATW process providing superior final product quality at minimized production time and cost. The computational time of the OTOM tool is in the order of magnitude of 1-10 s depending on the computational parameters. Inline process control requires a far shorter response time, however. Also stochastic process design will require a much faster model, as discussed in the following outlook.

7.2 Outlook for a fast process control tool and robust LATW process

In this section, the potential usage of the developed process simulation tool and results obtained in this thesis is described to create a fast model based inline process control approach and a robust LATW process in the future.

7.2.1 Surrogate model

The developed multi-physics based process models presented in this thesis can be coupled with a surrogate model in order to have a faster simulation of the LATW processes. The surrogate model should be simple enough to compute results in real processing time, but at the same time, should approximate the values as computed by the physics-based model of OTOM with sufficient accuracy. The time-dependent process and geometry related parameters can be considered in the surrogate model as input variables and the resulting temperature distributions in tape and substrate prior to or at the nip point could be the output variables. A flowchart of a surrogate model in which the laser power distribution is defined as the input variable and the nip point temperature is the output variable is seen in Figure 7.2. It is seen that the design of experiments are carried by using the OTOM simulation tool for the defined input and output variables. Subsequently, the surrogate model parameters are

Fig. 7.2 Flowchart for the creation and optimization of the surrogate model.

determined based on an optimization scheme in which the difference between the simulated and approximated output by OTOM and the surrogate model, respectively, is minimized.

7.2.2 Optimized process control

Once accurate surrogate models are developed, they can be employed by a model based feedforward and/or feedback control of the LATW processes. They can then be connected to the programmable logic controller (PLC) running the manufacturing processes. Based on the model predictions, a control algorithm can be employed to determine the optimum process settings to achieve the desired target temperature, e.g. at the nip point. Variations of the process parameters can be depicted and/or compensated via this control algorithm. A generic overview of the model based feedforward and feedback control is shown in Figure 7.3. The details of feedforward and feedback control are explained in the following.

i) Feedforward control: The temperature which is defined as the output is not measured in the feedforward control as seen in Figure 7.3a. An identifiable disturbance which can be

Fig. 7.3 Block flow diagram of (a) feedforward control and (b) feedback control.

predetermined or measured by a sensor is required to be fed into the optimizer constructed based on the predictive surrogate model. It was shown in Chapter 3 that the variations in the winding velocity, roller force and mandrel curvature influenced the nip point temperature significantly. These fluctuations or disturbances can be taken into account in the inline process control as indicated in Figure 7.3a on the left. Once the disturbance in certain process parameters is known, the surrogate model can be used to optimize the process parameters, e.g. the laser power and its distribution, to have a desired nip point temperature while satisfying the constraints. In the feedforward control, the information received from the sensor does not include temperature measurements. This approach is very similar to the study conducted in Chapter 6 on process optimization for the winding of a pressure vessel dome where the variation in the substrate curvature was predetermined. The advantage of this method is the independency of the algorithm on the measured temperature. However, any variation in the process temperature due to defects, gaps or overlaps in the already wound substrate is not addressed. Earlier work in this thesis showed the importance of these local variations and/or defects on the temperature development of the substrate (see Chapter 3). Hence, a more robust production process is potentially obtained if the available temperature data is included with a feedback control, as discussed next.

ii) Feedback control: The temperature can be measured via a thermal camera or a pyrometer where any process variation can be taken into account. In this case, the data received from the sensors includes the measured process temperature, as seen in Figure 7.3b. Any difference between the measured temperature and the target temperature can be compensated by adjusting the laser power, with an amount prescribed by the (approximate) surrogate model. A limitation of this approach is, for example, that the measured temperature could have some uncertainties due to the varying emissivity of the materials as a function of temperature in LATW processes. Dealing with uncertainties in these measured temperatures, but also, more in general, in any of the relevant material/process parameters determining the nip point temperature is of prime importance for the development of a more robust LATW manufacturing process.

7.2.3 Stochastic modeling

Any manufacturing process is influenced by intended and unintended variations in input variables, circumstances and materials. Stochastic modeling is an approach to capture and quantify the influence of (random) variations in input variables on the process studied. In this case the probability distributions of potential outcomes can be obtained by stochastic modeling based on randomized variations of the process models' input variables. Such a stochastic model can support the development of a digital twin of the LATW process. The

procedure to obtain the stochastic model can be executed as follows: first, the physics-based OTOM simulations are performed to consider geometries, material parameters, and lay-up in ideal conditions. For example, by using a constant ideal process lay-up speed, known material properties, etc. Then, a stochastic approach, such as Monte Carlo simulations, are performed to insert potential disturbances into the LATW simulation process to predict the deviation of the temperature outputs. The disturbances include e.g. gap, overlap, eccentricity and fiber movement, which influence the process and material parameters as observed in this thesis. The repetition of this procedure is necessary to ensure its reliability which can empower the role of the digital twin in the LATW processes. Successful implementation and validation of this approach can pave the road to further support the robust manufacturing of fiber reinforced thermoplastic composites made by LATW.

7.2.4 Process vs Performance evaluation

The local temperature distribution at the nip point described and predicted in this thesis can be linked to the resulting mechanical performance of the composites parts manufactured by the LATW process. The analysis of the nip point temperature is the first step to thoroughly understand, predict and control the mechanical performance by controlling the process. To illustrate, the effect of temperature spikes at overlap/gaps in the already wound layers on the performance of the manufactured product is required to be assessed to determine whether these spikes can be treated as noise or should be avoided by the aforementioned process control strategies. It should be noted that the mechanisms governing the mechanical performance (a.o. the development of the interface strength) are more complex than prediction and controlling of the nip point temperature. The incoming tape and already wound substrate may deconsolidate prior to the nip point [28] which affects the internal microstructure and thereby the material properties. The deconsolidated tape and substrate are to be reconsolidated after the nip point under the compaction roller. Here, the challenge is to remove the intra- and interlaminar voids present in the original material as well as originating from deconsolidation. In addition, the bond strength between tape and substrate develops by generation of intimate contact at the polymer-polymer interface and subsequent interdiffusion of the polymer molecules (healing), possibly interacting with crystallization processes. Accurately describing and modelling these mechanisms are beyond the scope of this PhD thesis and deserve to be addressed during future research towards performance optimization by means of process control.

Chapter 8

Conclusions and recommendations

This chapter presents the main conclusions drawn from the previous chapters and the future recommendations to improve the methodologies proposed in this thesis.

8.1 Conclusions

This thesis focused mainly on understanding, description and prediction of the governing optical-thermal phenomena in laser assisted tape winding (LATW) processes. The aim was to take the first steps in developing fast inline monitoring and control models for fiber reinforced thermoplastic composites manufactured by LATW. To this end, several aspects, which were not covered by the literature, were investigated as presented in previous chapters. The research work includes a multiphysics process model, its critical input parameters and its use for process optimization. The main conclusions of this thesis are listed below:

- The fiber content in thermoplastic prepreg tapes have an important influence on the absorbance and reflectance as well as the anisotropic reflection behavior.
- The process temperature is sensitive to the average substrate temperature that in turn is dependent on the local heating and cooling cycles induced by the LATW process.
- A larger coefficient of variation (COV) of the substrate temperature than the COV of tape temperature was found from the histograms of measured temperatures.
- The relation between process parameters and geometrical anomalies (surface features, eccentricity, unroundness) had a severe impact on the actual temperature in the process zone.

- The variation in the substrate temperature was found to be more severe than the tape temperature during continuous hoop winding mainly due to continued heating of the substrate.
- An increase in the pressure vessel radius results in a reduction of the process temperature due to the smaller laser incident angles and less absorption of the laser energy.
- An increase in the winding/placement angle results in higher temperatures for the tape and lower temperatures for the substrate.
- A reduction in tape temperature was found for a smaller mandrel as compared to a larger mandrel because some of the reflections from the substrate did not illuminate the tape.
- The tape and substrate temperatures were found to be less sensitive to a change in tape/substrate width as compared to a change in the winding/placement angle or the mandrel diameter.
- The sharp curvature change at the transition region from the cylindrical to the dome part of the pressure vessel results in a significant increase in the local process temperature.
- The LATW process can be optimized by including the shape of the complex tooling geometries through which the laser irradiation and temperature profiles change as a function of time.

8.2 Recommendations

Although several steps have been taken toward the in-line local LATW process model through the previous chapters, there are still some aspects that can be further developed. A general outlook and recommendations for future works are described below:

- As the tape material is melted during the manufacturing process prior to the nip point, optical properties of the tapes at temperatures above the melt temperature are recommended to be characterized in future research.
- It is recommended to address the effect of different fiber layups for the substrate on the temperature distributions by using the anisotropic reflection model within the OTOM tool.
- More accurate inline measurements with a real-time adaptive detection of the nip point location and a feedback temperature control system need to be developed to ensure

reliable measurement of the nip point temperature and to prevent undesirable variations in the measured temperature due to geometrical disturbances.

- The laser power distribution is recommended to be included in the process optimization as one of the design variables because the recently developed vertical cavity surface emitting laser technology allows to use a discrete laser power distribution.
- The minimum and maximum temperature in the substrate and tape are required to be defined as constraints in the process optimization framework in order to avoid insufficient and excess heating.
- To make the developed multiphysics process model computationally faster, surrogate models can be trained which can then be used for an inline process control and a stochastic process design.

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Publications

Journal papers:

1. Zaami A, Baran I, Bor TC, Akkerman, “Optical characterization of fiber-reinforced thermoplastic tapes for laser-based composite manufacturing”, Manuscript submitted in composite Part A, (*Chapter 2*).
2. Zaami A, Schäkel M, Baran I, Bor TC, Janssen H, Akkerman R. “Temperature variation during continuous laser-assisted adjacent hoop winding of type-IV pressure vessels: An experimental analysis”, Journal of composite materials. 2019 Nov, DOI.org/10.1177/0021998319884101 (*Chapter 3*).
3. Zaami A, Schäkel M, Baran I, Bor TC, Janssen H, Akkerman R. “A fully coupled local and global optical-thermal model for continuous adjacent laser-assisted tape winding process of type-IV pressure vessels”, Journal of composite materials, 2020 July, DOI.org/10.1177/0021998320944598 (*Chapter 4*).
4. Zaami A, Baran I, Bor TC, Akkerman, “3D Numerical Modeling of Laser Assisted Tape Winding Process of Composite Pressure Vessels and Pipes—Effect of Winding Angle, Mandrel Curvature and Tape Width”, in Materials, June 2020, DOI.org/10.3390/ma13112449 (*Chapter 5*).
5. Zaami A, Baran I, Bor TC, Akkerman, “New process optimization framework for laser assisted tape winding of composite pressure vessels: Controlling the unsteady bonding temperature”, Materials & Design, Sep 2020, DOI.org/10.1016/j.matdes.2020.109130 (*Chapter 6*).

6. Zaami A, Baran I, Bor TC, Akkerman, "Generic numerical optimization of laser source on helical laser assisted tape winding of composite pressure vessel and tubes", (Under preparation).

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1. A Zaami, I Baran, and R Akkerman. "Experimental and numerical analysis of laser reflection for optical-thermal process modeling of tape winding", 21st International Conference on Composite Materials, ICCM, Xian, China, 20-27th August 2017.
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