New process optimization framework for laser assisted tape winding of composite pressure vessels: Controlling the unsteady bonding temperature

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Abstract

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 80 °C 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 1.5 °C 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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1. Introduction

Laser assisted tape winding (LATW) and placement (LATP) are automated manufacturing techniques to produce high performance fiber reinforced thermoplastic (FRTP) composite parts. Some examples for composite products manufactured by the LATP process are pipes in oil and gas industry [1–3], low cost type-IV pressure vessels as storage tanks in the transportation sector [4] or over-wrapped pressure vessels for fuel tank applications in the aerospace industry [5,6]. 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 [7]. An in-situ consolidation of the FRTP 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 [8–10] as well as the product quality and performance of the wound or placed FRPT parts, e.g. the interlaminar bond strength of the deposited layers [11,12] and the interlaminar void content [13]. 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 FRTP tapes on complex geometries, e.g. dome part of a pressure vessel, the process temperature changes and an unsteady thermal history is present [14]. In addition, the process temperature is also influenced by the winding angle due to the change in the local geometry as shown in [15]. 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 FRTP composites. Thermal models were developed in [16–25] 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 [11,18,26–28] for the LATP process with flat tooling geometries and in [15,29–36] 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 FRTP 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 [21,22,37] to predict the final bonding quality and material properties of the FRTP composites produced by automated tape placement or winding processes. The optimum process temperature and its range were obtained based on the fracture toughness [38], the interlaminar peel resistance [39], the wedge peel strength [40] and the product quality [41] of the FRPT 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 [42] to achieve the required heat flux distributions for a given desired heating profile on a flat tooling geometry. In [43], 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 [14,44] 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 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.

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 Fig. 1a. The fiber volume content (FVC) of C/PA6 tape was 48% which was taken from [45]. 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 ($t_s$) were defined for the winding kinematics in which a length of $d t = 1.95$ mm tape was deposited on the substrate with a time increment of $d t = 39$ 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 Fig. 1b. The winding path began at $t_s = 1$ on the cylindrical part of the pressure vessel and continued on the dome part following a geodesic path until $t_s = 161$. The intersection of the cylindrical and dome part of the pressure vessel took place at $t_s = 77$ as seen in Fig. 1b. The position of the laser source with respect to the roller/tape orientation remained the same as reported also in [7,14]. 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 ($\theta$) and the distance to the substrate ($r$) are shown in Fig. 1b.

![Fig. 1. Schematic view of the winding path (a) and kinematics (b) on the pressure vessel for different locations. Note that the laser orientation (angle $\theta$) varies along the winding path from the start ($t_s = 1$) to the finish of the winding path ($t_s = 161$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).](image-url)

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normalized tooling surface curvature evolution as a function of ts for the nip point location are given in Fig. 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 Fig. 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 Fig. 2. Thus, the most critical location in Fig. 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 Fig. 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.

3. Numerical process simulation tool

A generic combined optical-thermal simulation tool was developed based on the work reported in [15] for LATP and LATW processes. This numerical process model was part 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 Fig. 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 Fig. 1). 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 2. The details of the optical and thermal models are explained in the following sections.

3.1. Optical model

A parametric 3D optical model with the ray-tracing approach was developed based on the generic model created in [15]. A schematic view of the model geometry is given in Fig. 5a. A global coordinate system denoted as $X$, $Y$ and $Z$ was used in the optical model. Here, $W_L$ and $R_L$ were the roller width and radius, respectively, $W_T$ and $H_T$ were the width and height of the laser source defined as a plane toward the nip line N1–N2, respectively. The contact region between the tape and roller was defined with the angle $\theta_0$. 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 Fig. 5b. The position of the laser source including the location $P_l(X,Y,Z)$ and orientation $\theta_l$ were defined with respect to the nip line N1–N2. The details of the optical model and its implementation can be found in [15]. The geometrical parameters used in the optical analysis are summarized in Table 1.

A uniform laser power distribution with a magnitude of $P_{l\text{max}} = 430$ 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 [15,31] 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 [26] 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 [29]. The refractive indices of the composite prepreg and deformable roller were taken from [46] with a value of 1.95 and 1.43, respectively. A total of 10,200 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 2, the laser irradiation and reflection on the substrate and tape at every time step ($ts$) were modeled based on the local surface curvature and laser orientation. The discretization of the winding path is illustrated in Fig. 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 $Ad$ which was determined based on the time increment ($\Delta t$) 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.

3.2. Thermal model

The tape and substrate geometry defined in Fig. 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 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 [15, 31]. The thermal computational domains for tape (2D) and substrate (3D) are depicted in Fig. 7.

The geometrical parameters can be found in Table 1. The governing equations used for the tape and substrate domains are given as [15]:

\[
\rho C_p \frac{\partial T}{\partial t} + v \frac{\partial T}{\partial x} = k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2}, \quad \text{Tape} \quad (1)
\]

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

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, $\rho$ 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 Fig. 7. Next to the heat flux boundary condition, a convective heat transfer was defined on these surfaces with the ambient air temperature ($T_{\text{air}}$) by assigning a convective heat transfer coefficient (CHTC) $h_{\text{air}}$. Similarly, a CHTC was used for the tape-roller interface ($h_{\text{roll}}$ with the roller temperature $T_{\text{roller}}$) for ($L_T - L_{\text{flat}} < x < L_T$) and the substrate-tooling interface ($h_{\text{tooling}}$ with the tooling temperature $T_{\text{tooling}}$) 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 [15,31]. 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 \( T_{nip} \) (see [15,31] for more elaboration on implementing boundary conditions).

A control volume based finite difference technique with upwind implicit scheme as used in [48,49] 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 2 which were determined based on the available data in literature [45].

### 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 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 (\( T_{ts} \)) and tape temperature (\( T_{ts} \)) along the nip line as \( N1-N2 \) seen in Fig. 5, i.e. \( T_{nip} = \frac{(T_{ts} + T_{ts})}{2} \) by assuming the heat capacities of the tape and substrate were comparable. The nip point temperature was defined in a similar way in [38,50] 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 \( T_{nip} \) and \( T_{ts} \).

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 [15,46]. An illustration of a typical heat flux and temperature distribution including the shadow region in the LATW and LATP processes is depicted in Fig. 8[15,46]. The time required for a material point to pass the shadow length is expressed as the shadow length duration, \( t_{shadow} \). Since the material point moved along the discretized thermal points on the winding path (see Fig. 6), the stepwise \( t_{shadow} \) was considered in the optimization problem. It should be noted that \( t_{shadow} \) 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 toward the nip point which results in an increase in \( T_{upper} \) 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 \( ts + t_{shadow} \) as shown in Fig. 8 due to the material advection. Hence, the optimization problem was constructed based on the design variable \( P \) at \( ts \), i.e. \( P(t) \) and the output variable \( T_{nip} \) at \( ts + t_{shadow} \), i.e. \( T_{nip}(ts + t_{shadow}) \). The corresponding SOP was formulated as:

\[
\text{Minimize : } f_1(P(t)) = \left| T_{nip}(ts + t_{shadow}) - T_{desired} \right| \\
\text{subject to : } \begin{cases} 
  g_1(P(t)) = T_{lower} < T_{nip}(ts + t_{shadow}) < T_{upper} \\
  g_2(P(t)) = T_{ts} < T_{upper} \\
  g_3(P(t)) = T_{lower} < T_{ts} < T_{upper} 
\end{cases} 
\]

where \( T_{upper} \) and \( T_{lower} \) were the upper and lower temperature constraints, respectively for \( T_{nip} \) and \( T_{ts} \). The process optimization problem defined in Eq. (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 \( T_{desired} \) and \( T_{upper} \) and \( T_{lower} \) were set to 270 °C, 380 °C and 220 °C, respectively, based on the experimental work done in [40] 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 [40]. 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.

![Fig. 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 Δt 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).](image-url)
The optimization procedure explained in this section is summarized by using a flowchart seen in Fig. 9. The SOP defined in Eq. (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 [51]. 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.

5. Results and discussions

5.1. Reference case

In this section, the process simulation results for the pressure vessel winding defined in Fig. 1 are presented. The total laser power remained constant \( (P = 430 \text{ W}) \) 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 [33]. 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 [33] for flat surfaces are shown in Fig. 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 [15,31]. The laser intensity for the tape was the highest \( (4.5\times10^5 \text{ W/m}^2) \) 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 Fig. 10a. The laser reflections coming from the substrate on the tape surface are visible at the location 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 Fig. 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 [52].

The absorbed laser intensity distributions on the surface of the tape and substrate predicted at different locations of the pressure vessel are shown in Fig. 11. From \( ts = 1 \) to \( ts = 48 \) corresponding to \( d = 0 - 93.5 \text{ mm} \), 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 \( 3.5\times4\times10^5 \text{ W/m}^2 \). 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 Fig. 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 \( d = 150 \text{ mm} \) where the substrate irradiation area was the smallest among all the time steps with the highest intensity value of approximately \( 8\times10^5 \text{ W/m}^2 \). The total irradiated area for the tape decreased from \( ts = 49 \) to \( ts = 77 \) due to the reduction in

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**Fig. 7.** Schematic view of the thermal domains for tape and substrate which were unfolded from the optical domain defined in Fig. 5.

**Table 2**

| Process/material parameters       | Symbol | Value       | Unit          |
|----------------------------------|--------|-------------|---------------|
| Composite thermal conductivity   | \( k_a \) | \( 5,0 \) | W/(m·K) |
| Composite density                | \( \rho \) | \( 1450 \) | kg/m³ |
| Composite specific heat          | \( C_p \) | \( 1600 \) | J/(kg·K) |
| Air heat transfer coefficient    | \( h_{air} \) | \( 10 \) | W/(m²·K) |
| Air temperature                  | \( T_{air} \) | \( 20 \) | °C |
| Roller heat transfer coefficient | \( h_R \) | \( 100 \) | W/(m²·K) |
| Roller temperature               | \( T_R \) | \( 20 \) | °C |
| Tooling heat transfer coefficient| \( h_{tooling} \) | \( 100 \) | W/(m²·K) |
| Tooling temperature              | \( T_{tooling} \) | \( 20 \) | °C |
| Incoming material temperature    | \( T_{incoming} \) | 20 | °C |

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**Fig. 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.

**Fig. 9.** Flowchart of the developed process optimization procedure.
the reflections coming from the substrate. After $t_s = 77$, 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 Fig. 3. Thus, the localization/intensification of the laser intensity on the substrate domain started decreasing after $t_s = 77$ as seen in Fig. 11 and diminished almost completely at $t_s = 90$. The tooling curvature also influenced the substrate shadow length prior to the nip point as seen in Fig. 12. The shadow length decreased to 1.95 mm for $t_s = 77 - 79$ where the highest tooling curvature took place as seen in Fig. 2. The obtained results in Fig. 11 were in accordance with the findings in [53] 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 Fig. 13. Three exemplary locations on the substrate including the inlet ($A_1 - A_2$ in Fig. 6), the nip point ($N_1 - N_2$ in Fig. 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, $t_s = 1 - 48$. Overall, the magnitude of the absorbed power by the substrate and tape was approximately 155 W and 105 W, respectively, for $t_s = 1 - 48$. 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 Fig. 13:

- From P1 to P2 ($t_s = 49 - 58$): 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 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.
The localized behavior of the absorbed laser radiation occurred again the lower part of the dome section of the pressure vessel where the substrate intensity had its maximum which was approximately \(T_{nip} = 77\) as shown in Fig. 13, the maximum temperature at the nip line occurred at a later stage in time, i.e. at \(T = 80\), due to the advection of the material during winding. After \(T = 80\), the substrate temperature at the nip line gradually decreased as illustrated for \(T = 85\) and \(T = 110\). The substrate temperature gradient at the nip point along the thickness was observed for the defined winding path in Fig. 14 which was approximately between 80 °C–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 Fig. 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 Fig. 14 by comparing the tape temperature distributions from \(T = 48\) to \(T = 80\). Similar evidence is visible from Fig. 13b where the maximum normalized intensity of the tape remained constant at a value of \(I\). 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 Fig. 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 \(T_{nip}^T\), \(T_{nip}^S\), and \(T_{nip}^F\) are shown in Fig. 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 Fig. 7. It is seen that \(T_{nip}^T\), \(T_{nip}^S\), and \(T_{nip}^F\) reached steady state temperatures of approximately 270 °C, 250 °C and 290 °C, respectively, with less than 2°C variation at \(T = 40\) and these temperatures remained constant until about \(T = 65\). The temperature trends were found to be very similar to the experimental measurements with constant velocity in [14] 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 \(T = 55\) in Fig. 15. The increased amount of heat accumulated due to tooling curvature as explained above and advected toward the nip point led to a significant temperature increase as can be seen clearly in the temperature distribution plots at \(T = 70\) and \(T = 77\). It also caused \(T_{nip}^T\) and \(T_{nip}^F\) to reach maximum values of approximately 350 °C and 460 °C, respectively at \(T = 80\). The tape temperature started decreasing from \(T = 61\) until \(T = 83\) due to the less reflections coming from the tooling/substrate. The minimum \(T_{nip}^F\) was calculated as approximately 250 °C at \(T = 83\).

The substrate temperature decreased gradually after \(T = 80\) 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 Fig. 15 that there was a less steep increase in the centerline substrate temperature at \(T = 110\) than at \(T = 85\). As the localized heating disappeared for the substrate after \(T = 110\) since the irradiated area of the dome section was relatively flat, \(T_{nip}^T\), \(T_{nip}^S\), and \(T_{nip}^F\) reached again a temperature plateau of approximately 275 °C. However, the reached plateau temperatures are somewhat higher than obtained for the cylindrical part (between \(T = 1\) and \(T = 48\)) because of the slight curvature of the dome section between \(T = 110\) and \(T = 161\).
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 Fig. 15 was minimized with respect to $T_{desired}$ by solving the SOP defined in Eq. (3).
The described optimization scheme in this paper searched for the optimum total laser power in each step to regulate $T_{nip}$ as shown in Fig. 17a. The tape and substrate absorbed powers and their corresponding maximum intensity values together with the substrate curvature are also shown in Fig. 17b and Fig. 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 Fig. 13 was employed in Fig. 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 Fig. 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 Fig. 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 $T_{nip}$, $T_{sub}$ and $T_{tap}$ together with the corresponding optimum laser power profiles and non-optimized $T_{nip}$, $T_{sub}$ and $T_{tap}$ are shown in Fig. 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 Fig. 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 maximum increase of approximately $1.5$ °C 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 $T_{nip}$ and $T_{nip}$ remained nearly steady. Afterward, $T_{nip}$ gradually decreased approximately to $220$ C and $T_{nip}$ increased to $320$ °C. It is seen that $T_{tap}$ 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 [40], 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 Fig. 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 Fig. 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. $t_s = 80$) 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 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.

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 into the optimization goal are suggested as future works as well in full-scale analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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