# IN-LINE PHYSICS-BASED MODEL SIMULATION FOR PROCESS MODELING OF LASER TAPE WINDING

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**ABSTRACT:** Fast temperature prediction in laser assisted tape winding (LATW) process is a pivotal factor for having an in-line monitoring model. The interaction from the laser input to the output temperature should be fast enough considering the physics-based strategy. As the laser tape winding is a fast process (typically more than 100 mm/s) with very high-temperature increase rate, changing the texture of materials is expected during the heating process which causes changing in final output temperature. The model-based control system in this research includes a three-dimensional (3D) optical model to simulate the laser intensity distribution on the surfaces and a 2D quasi-state thermal model. The predicted heat flux distribution is used in the 2D quasi-state fully implicit thermal model considering the advection term. Therefore, the procedure for calculating surface temperature can be performed in one computational step. Finally, the predicted temperature values can be sent to the PLC device via the ADS communication as a fast protocol to interact with the sensors and the industrial PC. The optimized laser intensity pattern, power, position and process velocity can then be calculated in the real-time.

**KEYWORDS:** Laser tape winding, Thermoplastic composite, Thermal simulation, Control sensor

## 1 INTRODUCTION

One of the breakthrough techniques to make fiber reinforced thermo-plasticc (FRP) unidirectional (UD) tapes is the Laser assisted tape winding (LATW). The traditional manufacturing of composites often involves thermosetting resins is slow, labor intensive and has to be post-processed. On the other hand, the LATW can get the cycle times down and there is potentially no post-processing necessary. Thus, the advantages make this process to be more attractive [1].

In general, setting up the production of a new part might take a considerable amount of time to find the optimum process parameters for enhanced product properties. In order to eliminate the expensive trial-and-error based design approaches for fast process and product design, the development of an in-line physics-based process simulation tool is essential for this process. Figure 1 shows schematic view of the LATW process. This process is described as applying heat and pressure to the thermoplastic tape. The steps that are taken are thermal softening of the material, intimate contact, and healing of bonded materials. Softening is a result of heating the surface of the tape and the laminate with a laser source. The temperature and pressure at the interface lead to interdiffusion of polymer chains on the contact area, which can be defined as healing for quantifying the quality of the product. Thus, the thermal history of the interface is considered to be a key parameter [1]. As a matter of fact, the important aspect of this process is the fusion bonding during the consolidation of tapes for having a high-quality product. This can be controlled by an accurate temperature which is the point of interest in the current study.

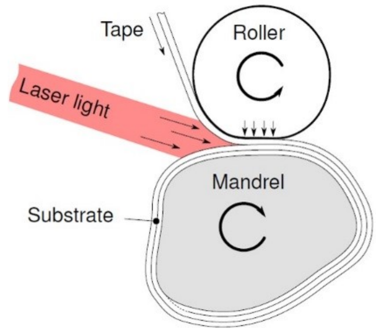


***Figure 1:*** *Schematic of LATW process.*

Several studies have been performed regarding the experimental and the numerical modeling of the LATW or laser assisted tape placement (LATP) processes. The attention here is on the studies considering coupled optical-thermal models [1–4].

The temperature prediction for the LATP was developed in [1] where a ray-tracing method together with

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a one-dimensional (1D) thermal model was used. Another study was performed by Stokes-Griffin [2] who developed a more detailed model for the LATP. In the LATW, a cylindrical substrate is used with different geometrical orientations (oblique angle) and a more complicated optical-thermal process model should be taken into account. In this regard, another study was carried out in [5] to simulate the effect of non-specular reflection model. It was shown the geometry complexity can play an important role on the energy absorption/reflection and subsequently temperature distribution. In addition, there is a lack of a general optical model that considers the effects of an oblique angle and winding direction in the literature to be integrated into an in-line monitoring control setup.

The main goal of this paper is to show the strategy to have a fast and accurate model for in-line monitoring and quality assurance which is a part of EU funded ambliFibre project. The process control is supported by the dedicated simulation model which is designed to perform complex setup configurations of the LATW process. Regarding the interaction of thermo-optical model with the sensors, the ADS communication is constructed to link Matlab and TwinCAT variables. The final optical-thermal model can be able to compensate the difference between the predicted and the measured values of the nip-point to have better product properties with minimized energy consumption.

## 2 METHODS AND MATERIAL

### 2.1 PROBLEM DEFINITION

The physics-based model for the LATW process requires advanced considerations which are a complicated procedure, from the micro scale to the macro scale simulation. Generally, the behavior of the processed material and its translation to the final product quality is time-consuming. Thus, such strategy needs to be defined in order to accelerate computational time to obtain an applicable model for implementing the control system. Here, the simulation is divided into the several blocks which are optical, thermal, optimization and ADS communication.

### 2.2 METHOD

The accurate temperature prediction of tape surfaces in the LATW process is highly dependent on the optical behavior of the thermoplastic and the translation of the optical energy to the boundary conditions of the thermal model. Regarding the optical modeling, the ray-tracing method is used [3–5]. This method is summarized into the following of a ray and find an intersection with objects in the LATW. In addition, only the first reflection is calculated as the much of energy is absorbed in the first and second interaction with the material [5]. In order to have an acceptable resolution, it is needed to have more than 1000 rays [3] which is time-consuming. However, it is known that the geometrical configuration of the laser (position, angle) device during the process is not changing. Thus, all the calculations related to the optical model can be executed as an initialization step and the results (intersection points and corresponding energy) for each object can be saved. For the sake of computational efficiency, there are some key points for the optical modeling which can be summarized as below:

- Only considering up to the first reflection
- Calculating intersections based on analytical expressions for the surfaces
- Defining a unique axis systems for each object
- Smart programming for decision making of intersected object

For calculating the nip-point (bonding region) temperature, it is necessary to know the history of each particle of the tape through the time. However the process is not steady-state in reality because of the presence of the velocity term, but thanks to the Eulerian framework, it can be considered as a quasi-state problem by including the velocity into the diffusion equation (EQ.1). Therefore, the predicted heat flux distribution from the optical model is used in a 2D quasi-state fully implicit thermal model which considers the advection term to calculate the temperature distribution.

$$V\frac{\partial T}{\partial x} = \alpha(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}) \tag{1}$$

Where $V$ is the velocity, $\alpha$ is the thermal diffusivity, $T$ is the temperature, and $x, y$ are the coordinate axis. Implementing this procedure, the computational steps reduce to one and the time increment convergence disappears. However, the only difficulty of this framework is the hyperbolic nature of the governing equation. Such techniques like SUPG (Streamline Upwind Petrov-Galerkin) method is used to prevent instabilities in the numerical convergence [6–8]. Running the in-house thermal model which was coded through FEM (finite element method) procedure in Matlab takes 10-100 millisecond (the different acceptable mesh size) with a home PC configured with Core i7 @3.4 GHz. Thus, still, some simplifications should be considered here to reduce this time to order of magnitude approximately 1 millisecond as it is the desired value for the in-line machine control.

Furthermore, there are some key points for the thermal modeling which can be summarized as below:

- Fast assigning the optical energy to the thermal points (distance-based weighting function)
- Translate boundary conditions of the curved surface to the unfolded thermal model to eliminate through-the-thickness direction in z-coordinate (3D to 2D)

• Engaging velocity into the thermal solver (Eulerian frame work)
• Smart indexing of the points for faster access to the data

In order to use the control program designed in Matlab with the real machine after successful tests in simulation, the developed algorithms can be programmed manually in real-time-capable languages like PLC code. Communication of sensors with the industrial PC is carried out by the TwinCAT software as a PLC. Automatic conversion of the already implemented algorithms into real-time-capable program modules needs a fast and reliable connection between the simulation software and the PLC. For establishing a connection from Matlab to the TwinCAT program, ADS communication was chosen as a fast protocol to transfer data. Corresponding variables in both programs are then connected. In addition, to use the possibilities of the ADS-DLL library, MEX-files were used to have a faster computation and more stable connection.

All the aforementioned procedure can be optimized to acquire best variables for the desired healing condition like specific temperature near the nip point at which the incoming tape is consolidated with the substrate as seen from Figure 1. Since this process needs a different kind of objectives for having the best quality product, a multi-objective genetic algorithm is used which is combined with the optical-thermal model. The Pareto designs are the results for each optimization setup. Figure 2 shows the flowchart of the process simulation model.

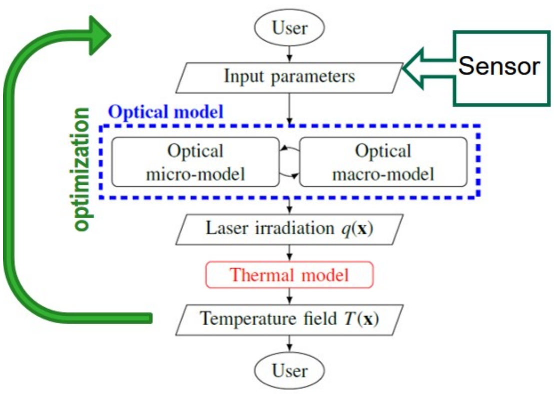


***Figure 2:*** *Flowchart of the LATW process model.*

## 3 RESULTS AND DISCUSSION

Here, the preliminary results of the model and the developed software are demonstrated. It is intended to show that the proposed optical-thermal model is a computational platform which enables the LATW process control. Figure 3 depicts the optical objects in the LATW process and how the laser rays hit the objects. All the geometrical parameters can be changed by the user at the initialization step. Furthermore, the optical-thermal results can be demonstrated at the same time in a figure with the distribution of the temperature on the surface of tapes. Nevertheless, this integrated optical-thermal program can also be optimized in any other software.

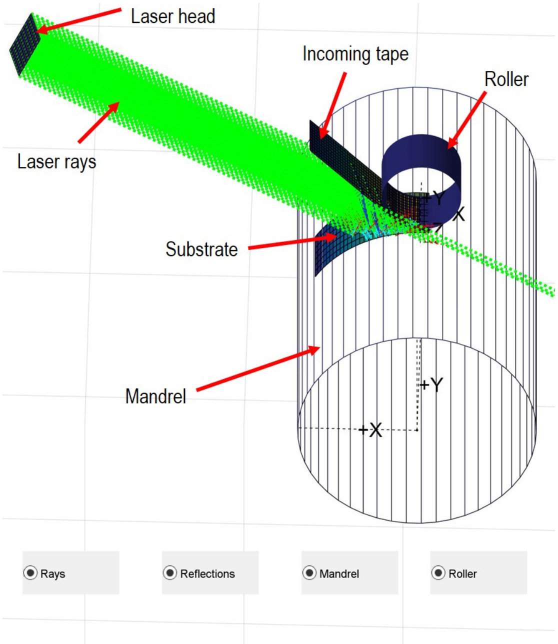


***Figure 3:*** *Objects in the developed process model.*

Figure 4 shows the heat flux and temperature distribution on the surface of substrate and tape. As it is seen, the resolution of the temperature distribution is far better than the one of intensity heat flux. The reason is the diffusion effect and the integration of field parameter, which is the temperature here, through the whole domain. Besides, for the sake of convenience, an easy-to-use interface was designed to provide a clear view of the process inputs and corresponding results. Figure 5 shows this graphical interface which is integrated as a stand-alone software.

## 4 CONCLUSIONS

The optical-thermal simulation model was defined for communicating with the industrial PC and sensors. The focus was on the capability for the interaction of fast simulation model with the sensors to obtain in-line results. To reach that goal, some suitable and practical methods for each section of simulation model were introduced and implemented based on the efficiency of the control model. It brought us to this end that still some other simplifications regarding the thermal model and ways to simplifying boundary conditions should be figured out. Additionally, the sensitivity analysis should be performed to verify current and future assumptions for the final in-line monitoring control model.

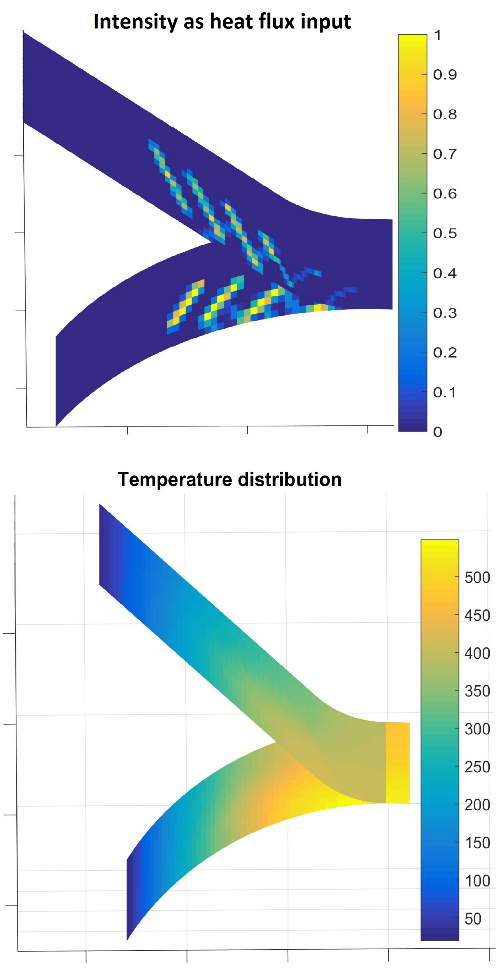


*Figure 4: Heat flux and temperature distribution.*

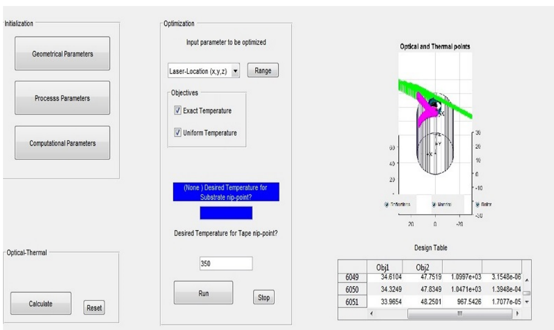


*Figure 5: Graphical interface of the developed software for LATW process.*

## 5 ACKNOWLEDGEMENT

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