ADVANCED SIMULATION OF THE LASER-ASSISTED TAPE PLACEMENT PROCESS

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Abstract
This article takes place in the context of modeling the laser assisted tape-placement process of a long-fibre reinforced thermoplastic matrix composite. In order to link the parameters of the process to the quality of the fabricated part, a thermo-mechanical model has to be elaborated. Thus, the present study focuses mainly on the estimation of the temperature field and the process-induced residual stresses.

1. Introduction

The laser-assisted tape placement (LATP) process is an automated composite manufacturing technique often quoted for its potential ability to produce composite parts with an in-situ consolidation, which avoids an expensive time and energy consuming step of post-consolidation. Within a cost reduction strategy, this process naturally appears to be very attractive. But in order to be competitive, it needs to ensure a certain level of quality of the fabricated part.

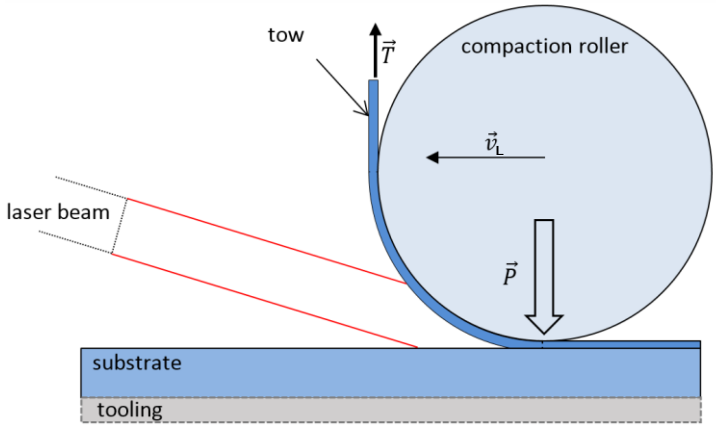

Figure 1. Illustration of the laser-assisted tape placement process.

During the process, a fibre-reinforced composite is continuously laid-down and consolidated onto the previously laid tapes, as illustrated in Fig. 1. While the tape is heated up by the laser, and supports the roller pressure and the tension, it is bonded to the substrate. This interlaminar bonding occurs in two coupled steps. Firstly, the intimate contact between the two surfaces we want to bond has to be achieved, and secondly, the diffusion of macromolecules across the interface unifies the two parts. By additively laying a multitude of layers, a composite part with the desired mechanical properties is manufactured. We should notice that the prediction of the quality of the bonding, for which the mechanical interaction between the roller and the tape, as well as the flow of the tape under the compaction roller should be modeled, is out of the scope of this study.

The differences in the thermal expansion coefficients between consecutive plies, and the mechanical loading of the tape combined with the bonding prevent a stress-free cooling process. The evaluation of the residual stresses is crucial since they have a strong impact on both the mechanical properties of the composite, and on its final geometry due to the so-called springback. This evaluation constitutes the main goal of the present study, and the step-by-step development of the thermo-mechanical model of the LATP process is the outline of this paper.

2. Thermal model

Within this study, a 2D model is established in a frame attached to the laying head, which is supposed to translate at a constant velocity. This hypothesis is correct only far from the edges. In such a frame, the material is convected with a velocity equal to the opposite of the velocity of the placement head, and the equation to be solved writes

$$\rho \cdot C_p \cdot \mathbf{v} \cdot \nabla T = \nabla \cdot (\mathbf{K} \cdot \nabla T) \tag{1}$$

where ρ is the density of the material, C_p its specific heat capacity, and **K** the conductivity tensor. At the moment, all these parameters are considered as being independent on the temperature, so that Eq. (1) is linear.

The heating of the composite by absorption of the wave emitted by the laser should be carefully modeled. In the case of a highly dense and absorbing long-fibre reinforced thermoplastic, it seems to be reasonable to treat it as a surface effect. Depending on the ratio between the wavelength and a characteristic size of the fibres (i.e. diameter), a Mie scattering regime could govern the reflected wave, making the geometrical optics hypothesis not viable. Thus, a promising modeling strategy in the case of a negligible transmitted wave would consist in first evaluating the composite's radiative properties, and secondly implementing an appropriated optical model. Even if some authors investigated this complex aspect experimentally [4], a complete set of such properties are not available in the literature. As no experimental determination has been yet undertaken, an insufficient but still available optical model based on the geometrical optics hypothesis has been implemented [3].

A lot of different thermal models of the process under study are proposed in the literature. The development of it [1,2,5] will not be detailed in the present analysis. Its main point consists in its multidimensionality. Within the Proper Generalized Decomposition framework [1], the temperature field can be computed for any value of the laying head velocity or the laser power, which is not possible using a classical meshing technique. The numerical approximation of the temperature field follows Eq. (2) and is associated to and an adapted test function, defined by Eq. (3).

$$T(x,y,v_{Head},p_{Laser}) = \sum_{i=1}^{i=N} X_i(x)\cdot Y_i(y)\cdot V_i(v)\cdot P_i(p) \tag{2}$$

$$T^* = X^*\cdot Y\cdot V\cdot P + X\cdot Y^*\cdot V\cdot P + X\cdot Y\cdot V^*\cdot P + X\cdot Y\cdot V\cdot P^* \tag{3}$$

Then, the solution is computed using an enriching loop, where a functional product is added to the numerical solution. This functional product is calculated with an alternating fixed-point strategy, where each function of this product is computed, alternatively, until convergence is reached.

3. Thermo-elastic model

A first step towards the modeling of the establishment of residual stresses during the LATP process has been set up [1]. Within this model, the mechanical equilibrium which takes under consideration the continuous welding of a unique ply over a ply initially at rest has been solved. The frame considered is not attached to the head, but to the tooling, and the matter is not convected anymore. The main difficulty here consists in the evolution in time of both the geometry under study, due to the welding of the tape, and of the temperature field, which translates due to the movement of the laying head. Capturing this evolution implies to have an incremental approach. As illustrated in Fig. 2, at each time increment, few nodes are added to the welded zone, the nip-point is translated, as well as the temperature field, and the mechanical equilibrium is solved. Then, increments after increments, the residual stresses develop within the composite. It should be noticed that the only external force applied on the material is the tension in the tow. The mechanical interaction between the tow and the compaction roller is not taken under consideration here.

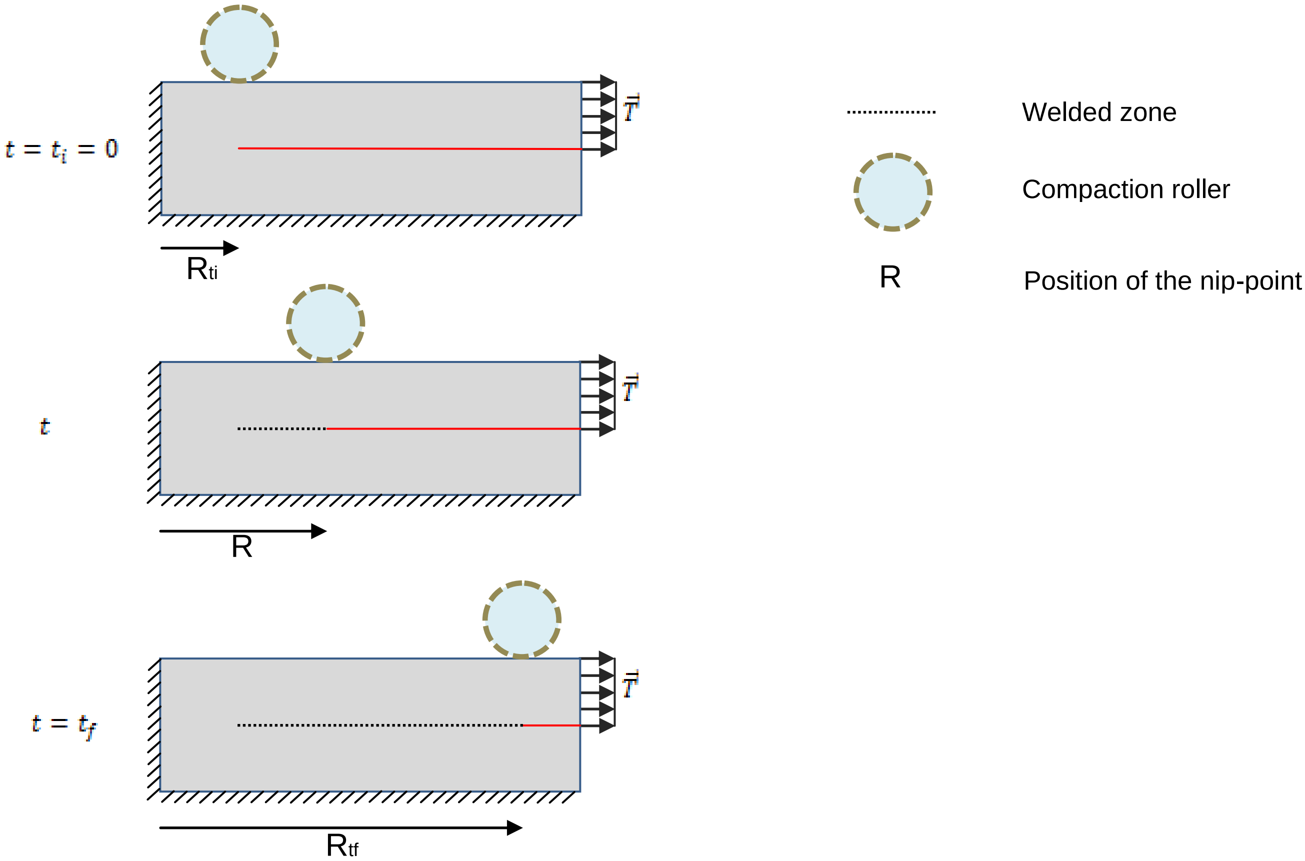

Figure 2. Illustration of the iterative thermo-elastic model of the LATP process

But in order to capture correctly the final state of stress, the calculation has to satisfy two very important aspects. Firstly, the computational domain has to be long enough, such that a certain region must see the laser coming, heats up, and then cools down to the room temperature. And the length of material affected by the heat source might be long, especially for a high laying velocity. Secondly, the time increment of the calculation has to be as small as possible to catch accurately the continuous welding phenomenon. Finally, these two aspects explain why this computation might be too much costly [2].

Avoiding these difficulties is possible if the mechanical equilibrium is solved in the frame that has been used within the thermal model. In this frame, objectivity must be carefully addressed because of the large displacements involved. Thus, a hypoelastic law is more adapted, and the equations to be solved, related to the mechanical equilibrium and to the constitutive law are far more challenging. Nevertheless, a convenient numerical strategy has been established, and both the unsteady velocity and stress fields have to be computed.

Before developing this numerical strategy on a representative LATP process model, these computations have been made on a simple test case: a 2D tensile test of a homogeneous material in a frame of reference translating at a velocity $\vec{v} = -v_D \vec{i}$ with respect to the frame attached to the material. This test case is illustrated in Fig. 3. A rectangular spatial domain $\Omega = \Omega_x \times \Omega_y = [0,3] \times [0,1]$ is discretized into 48 square elements, and submitted to a tension on its left hand side. This tension naturally appears in the weak form of the equilibrium equation. Concerning the constitutive equation, a boundary of the domain is either an inflow boundary, or an outflow boundary. As the velocity is imposed on the right hand side, only the top, bottom, and left hand side boundaries have to be carefully specified, depending on the local value of the velocity field on these boundaries. Unfortunately, even if only the normal projection of the stress tensor is known on these domains, the whole stress tensor has to be specified through the weakly imposed inflow condition.

Figure 3. Tensile test in a translating frame

After having reached the steady state, the relative increments between v^{n+1} and v^n, and between σ^{n+1} and σ^n are lower than 10^{-13}. The final state of stress and the final velocity fields correspond to the analytical one. For any objective derivative of the stress rate, the final fields are homogeneous and such that $\sigma_{xx} = \sigma_T$; $\sigma_{xy} = 0$; $\sigma_{yy} = 0$; $v_x = v_D$ and $v_y = 0$. Our numerical approach allowed us to recover exactly the velocity and the stress fields which correspond to the true elastic response of the material.

Finally, this unsteady hypoelastic model should be enriched to capture the establishment of thermal induced residual stresses, in a frame attached to the laying head, taking under consideration:

- the anisotropy of the material ;
- the presence of the discontinuity between the tow and the substrate ;
- the addition of the thermal loading ;
- the temperature dependence of the material properties.

4. Conclusion

In conclusion, a thermo-elastic model of the development of the residual stresses during the LATP process has been elaborated. While the multidimensional thermal model gives the value of the temperature field for any value of laser power and laying velocity, the 2D thermo-elastic model cannot provide yet accurate results with a reasonable computational cost. This difficulty has been overridden through the definition of an innovative non-linear and unsteady hypoelastic model. Even if it has only been solved on a simple test case, a staggered scheme has generated promising results. Naturally, in order to make the model as much representative of the LATP process as possible, future work is in progress concerning the complex laser-composite interaction, the experimental validation of the multidimensional thermal model, and the development of the thermo-elastic model.

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