AUTOMATED TAPE LAYING (ATL) PROCESS SIMULATION THROUGH 3D THERMO-MECHANICAL MODEL

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Abstract
The present paper describes the current state of work done during the STELLAR project on the ATP/ATL simulation. To assess the welding quality of the thermoplastic tapes, the computation of the contact pressure, the temperature and the phase evolution in the matrix (evolution the degree of crystallinity) are first importance. In the present paper, a two steps approach is described to simulate the process, and we especially focus on the temperature field history assessment. In the first step, the heating flux boundary conditions imposed by a laser to the tape, the head-tool and the support is assessed thanks to a ray tracing model. Then these heating boundary conditions are used in an explicit approach to solve the 3D thermo-mechanical problem.

1. Introduction

Driven by the future environmental standards, transport industries look for CO2 impact reduction of their vehicles. The aim of STELLAR project is to develop a manufacturing process for high-speed placement of fibre reinforced matrices, in selected locations of a composite structure and to provide the optimum reinforcement, weight and cost profile within a part. The global project focuses on the Automated Tape Laying (ATL) process to selectively place reinforced thermoplastic tapes following 3 manufacturing routes: selective reinforcement of existing components; direct additive manufacture of components; manufacture of selectively reinforced tailored blanks for compression moulding.

In the ATL process as sketched in Figure 1, a tape is placed and progressively welded on the substrate [1, 2, 3, 4]. By laying additional layers in different directions, a part with desired properties and geometry can be produced. However, the welding of the layers requires physical conditions, and most important among them is the permanent contact and the temperature required to ensure diffusion between the macromolecules. Moreover, precise diffusion of the macro-molecules through the welded interface, which characterizes a correct welding quality, takes time. This is a crucial question to increase the speed of the process. Due to low thermal conductivity of thermoplastics, higher temperatures can be reached at the interface with local heating. Thus, the bond strength development process [5], as well as other physical processes such as residual stresses development [6], void dynamics [7, 8], crystallinity [9, 10], and degradation [9] are all strongly linked with the specify temperature history.

Heat sources utilised for TP-ATP include hot gas torches, direct flames and lasers. The convective mode of heat transfer for the torches and direct flames limit the surface heat flux, restricting the maximum placement rate. On other side, more recently diode lasers have been adapted due to high efficiency, near instantaneous response and the ability to deliver higher heat fluxes [11]. Large homogeneous rectangular

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spots can be produced by compact optical modules, resulting in uniform, progressive heating across the length and width of the tape, increasing the dwell time and thus the bond quality. For ATP using a nip point heating strategy, the laser is aimed into wedge shaped cavity formed by the feed tape and the substrate. The laser strikes both surfaces with an oblique angle, resulting in potentially significant levels of reflection. As a result, the laser beam does not directly irradiate the substrate and the tape immediately before the nip point, potentially creating a shaded region [4, 12]. Previous studies indicate that due to rapid speed of the process, such a shadow would result in a significant temperature drop [12]. However, the oblique angle of the laser could lead to a significant reflections that would result in some unknown degree of indirect irradiation of the shaded region. It is therefore of interest to model the interaction between the laser and the parts to predict the level of irradiation and as a consequence, the temperature history.

One of the objectives of the project is to enhance the modelling tools to support the development of these tape deposition technologies [7, 11, 13, 14]. Based on the experience in metallic parts welding simulation [15], in composite manufacturing simulations with complex kinematics [16] and in thermo-forming [17], ESI Group works to model these complicated tasks. These ESI developed models will include the kinematics of the tape-laying, simulation of the heating of the tape, a thermo-kinetic module, compaction, bonding and finally a residual stresses evaluation. The present paper describes the current state of described developments for the ATL simulation. Firstly a laser model is presented which is used to assess the heating boundary condition imposed to the tape and the tools; then secondly the 3D thermo-mechanical model used to simulate the ATP process with the previous assessed heating boundary conditions is presented.

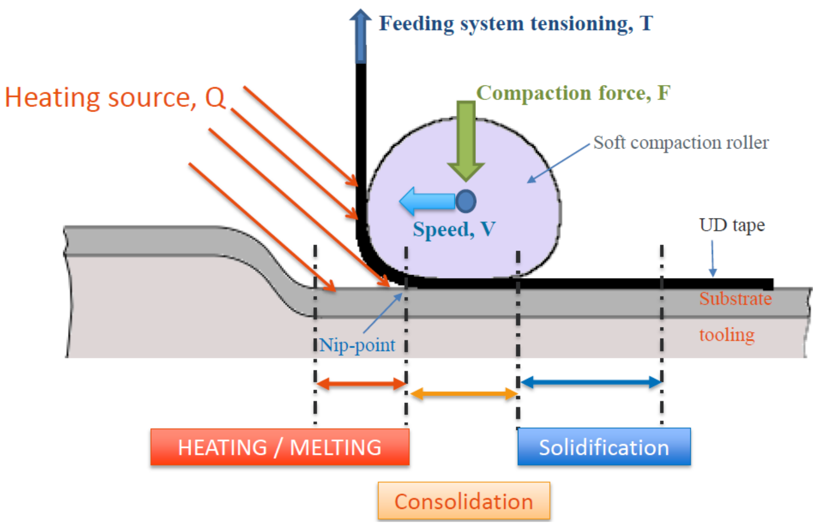

Figure 1: Sketch of the Automatic tape placement process with some of the complexity of the physics to be modeled.

2. Laser modeling

The laser was modelled thanks to the ray tracing method [12, 18]. This method is usually used in 3D image rendering. It is very close to the physics of light propagation where a ray can represent the path of a photon. Ray tracing allows the simulation of a wide variety of optical effects such as reflection, refraction and absorption.
Transmittance and reflectance measurements were performed on different TP-UD carbon composite materials in [4, 12] with spectrophotomer devices. Each time, the transmittance was found to be

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negligible for all the wavelengths of the laser ligth. In the optical model, the energy conservation is then simplified and reduced to Eq. (1):

$$A = 1 - R \tag{1}$$

Where A and R are respectively the absorptance and the reflectance values. The reflectance is calculated from the Fresnel equations with specular reflection assumption. The reflectance of s- and p-polarized light yield to the Eq. (2) and (3):

$$R_s = \left(\frac{n_{part} \cos\theta_i - n_{air} \cos\theta_t}{n_{part} \cos\theta_i + n_{air} \cos\theta_t} \right)^2 \tag{2}$$

$$R_p = \left(\frac{n_{part} \cos\theta_t - n_{air} \cos\theta_i}{n_{part} \cos\theta_t + n_{air} \cos\theta_i} \right)^2 \tag{3}$$

In which the angle of incidence θ_i and the angle of transmission θ_t are defined as shown in Figure 1.a and evaluated with the Snell's law in Eq. (4):

$$n_{part} \sin\theta_i = n_{air} \sin\theta_t \tag{4}$$

With n_{air} the refractive index of air, equal to 1, and n_{part} the refractive index of the medium (associated to the part impacted by the incident beam). In the considered simulation, the various mediums are composite for the tape and metallic for the tooling. However, for sake of simplicity in this first work n_{part} is equal to 1.8 for all the parts. It is the value measured for TP-composite in [1]. Moreover, it is assumed that the light is unpolarised, meaning that the reflectance can be assessed as the mean of R_s and R_p (Eq. (5)):

$$R = (R_s + R_p)/2 \tag{5}$$

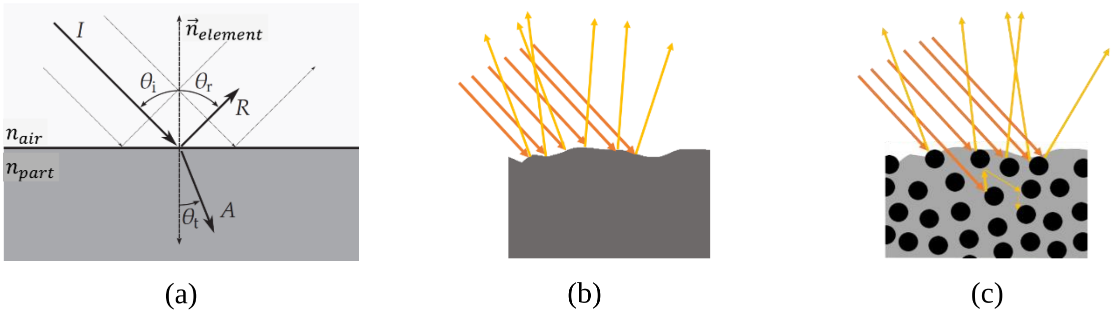

Figure 2: (a) Snell-Descartes law representation for a specular reflection type; (b) Lambertian reflection type (diffuse one); (c) Interaction of light with the composites: anisotropic behaviour.

The optical behaviour of the TP-UD composites shows a strong anisotropic behaviour as highlighted in [4, 12]. In these papers, a laser beam with a fixed angle of incident was spotted on a sample with fiber angle varied from 0 to 90°. The scattering behaviour for UD composite tape is anisotropic and changes from a crescent shape when the beam is aligned with the fibers to a vertical line when the sample is positioned perpendicularly. For transparent resin such as PEEK and carbon fibers, the scattering behaviour would be dominated by specular reflections from the individual carbon fibers as shown in Figure 2.c. While this behaviour could have a great influence on the heating of the tape by the laser, this first laser model only considers isotropic specular reflection behaviour of the composite surfaces.

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More advanced interaction model as the MHC surface model can be found in [12]. In future work, more complex optical behaviour of the composites will be studied.
Besides, we only considered a simplified source with a collimated beam and constant power profile. However, experimental observations have shown that there is significant divergence of the laser beam. Again, if needed, this effect of the optical source would be taken into account in future works.
In the present approach, the laser simulation aims to calculate the heat flux which have to be imposed at the nodes of the thermo-mechanical model for the simulation of the ATP process. Thus, it is the same mesh used for this ATP simulation that is used in the present laser simulation. For each beam ray which impact an element of the model, the absorbed power is divided between the nodes of this element.

3. Thermo-mechanical analysis with tool kinematics

3.1. Explicit simulation in PAM-FORM 2015

In previous work [19], a steady-state approach has also been considered, but in the case where the kinematics of the tool cannot be reduced to a steady-state, this approach is not available anymore. There are various cases where the steady-state assumption is not valid:

- With a change of velocity of the tool;
- With a more complex path than a long translation, circular or helical path;
- When the effect of steering and wrinkling are studying;
- In the case of multi-deposition of tapes with a short time between each pass, meaning that the previous added heat flux has not vanished before the new pass of the tool;
- Etc…

In these cases, an explicit scheme can be more appropriate to take into account the various kinematics and the time dependent effects during modelling. In the present paper, the coupled thermo-mechanical problem is solved in the same time with the ESI's PAM-FORM 2015 Solver. For time CPU optimization, the composite tape is modelled with shell elements.

3.2 Mechanical model

The deposition of one tape is decomposed in 2 phases as shown in Figure 3:

- The first phase corresponds to the beginning of the process when the head-tooling puts on compression the tape and the support.
- The second phase corresponds to the deposition itself and takes into account for the kinematic of the tool.

In this early study, the kinematic is kept simple and corresponds to the deposition of a tape onto a flat support. In the second phase, for stability consideration of the simulation, there is no compaction force applied to the roller. Instead, the normal displacement of the roller to the support is blocked (keeping the compaction force applied to the tape which was introduced during the first phase). The complex kinematic of the tape is described thanks to the kinematic of the roller associated to the contact interfaces between the parts: between the tape and the roller, between the tape and the support, and between the roller and the support.

The feeding system is modeled thanks to a bar element with a non-linear behavior insuring both the tensioning of the tape and the damping of unwanted exciting modes. Same approach has been used previously for the feeding system in braiding simulation [16].

The material used for the composite tape is material 140 for shell element, which is a material dedicated to composites in forming simulations when using PAM-FORM. It is an orthotropic material which can model fabrics and UD reinforcements. The only difference between these two modes is the second fibre direction computation. For fabric, the fibre directions follow the deformation of the elements whereas the UD mode assumes that the second fibre direction remains orthogonal to the first fibre direction [17]. This material model is a non-linear elasto-plastic material for which temperature,

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strain rate and curvature dependency can be added. There is also a damage behaviour option, but for now it is not relevant in this process model. The following behaviour is defined through the material input:

- Tension and compression deformation in fibre directions;
- In-plane shear deformation;
- Bending deformation in fibre directions;
- Thickness deformation through normal pressure.

In PAM-FORM 2015, it is possible to use look-up tables to define material input. Look-up tables allow introducing of dependency for the material parameters. This new feature will simplify a lot the material characterization of the material.

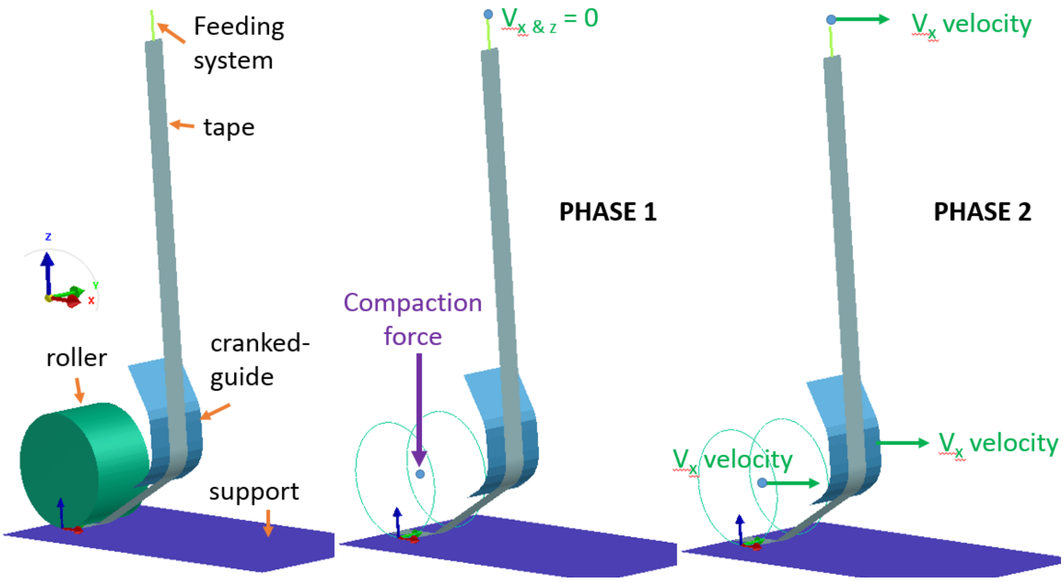

Figure 3: Explicit thermo-mechanical model. Each tape deposition is decomposed in 2 phases: phase 1 - roller compaction / tape tensioning phase, then phase 2- the deposition with the tool kinematic

3.3 Thermal model

One of the main difficulties is to apply sliding thermal boundary: the heating source (the laser for instance) is attached to the tool and moves with the tool. So all along the deposition of the tape, the regions of the tape and the support which are irradiated evolve with time. It is the same things for the roller if its rotation movement is taking into account. In the present paper, numerical rigid surfaces have been created which follow the same kinematic than the head-tool, and on which the heating boundary conditions previously calculated are applied, as shown on Figure 4.b. The heating flux is then transfered to the other parts by the mean of thermal contacts. As shown on Figure 4.b, 4 heating surfaces have been used for respectively the roller, the tape, the support and the cranked guide parts. Additional thermal contact interfaces are defined between the various parts (tape/support, tape/roller, and roller/support) so that the heat flux can be exchanged between these parts.

3.4 Some results

A dummy model was established to verify the feasibility of the simulation. In a first step, the laser simulation has been performed as shown on Figure 4.a. A square shape source has been used, with a dimension of 40x40 mm² and an orientation of 15° with the support. A cranked-guide is used to reorient the tape before reaching the roller, in order that the tape made a 30° angle with the support. A power of 1000 W has been used for the laser, but no dissipation are considered here. As shown in Figure 4.a,

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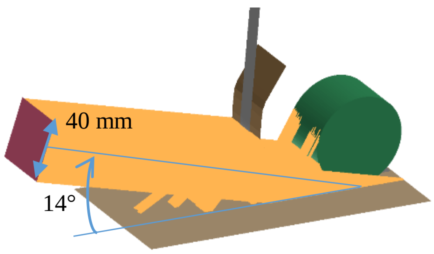
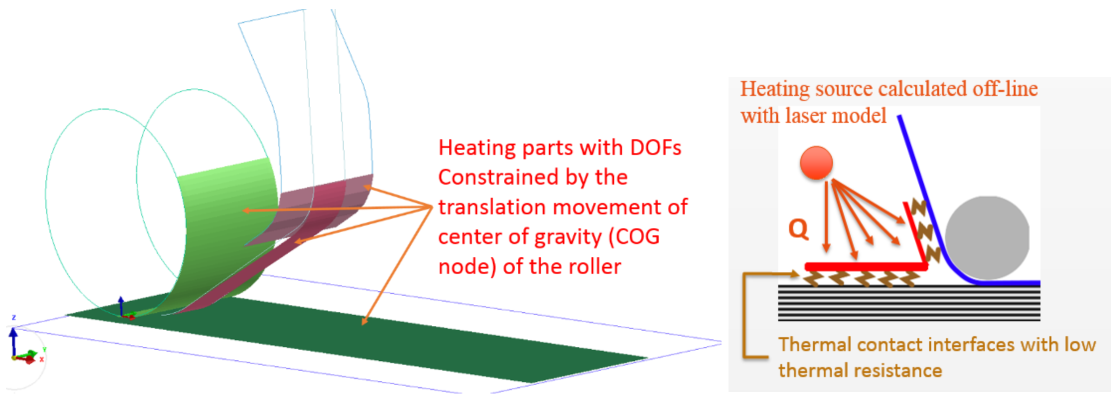
some rays impact the knee of the guide and reflect on the support. However, due to the rough discretisation of the guide mesh, the direction of the reflection along the knee is not continuous, as it is depending on the normal of the impacted element.
In Figure 5, two ATP simulations have been performed to evaluate the effect on the CPU time and the results: in the first one, the rotation of the roller along its axis is blocked, while it's free in the second. For the two cases, the roller is steel-like and thus modelled as a rigid body for which all the DOF are controlled by its center of gravity. For the second simulation, a coulomb friction coefficient of 0.15 is added between the roller and the support, as between the tape and the roller, in order to enable the roller rotation during the deposition. For 2300 s of process time, on a Intel(R) Xeon(R) CPU E5-2650 v3 @ 2.30GHz machine, the elapsed times for the simulations running on 4 cores are respectively 2:58:25 and 3:09:03, which is very close. Yet, the simulation time is may not be fully optimised and can be decrased. However, it can be seen that the convective effect of the rotation of the roller cannot be negligible in the simulation, at least to evaluate the maximum temperature peak. Indeed, at 1920s of the process, there is a difference of more than 100°C for the maximum temperature. Last, it can be said that for this model case, the heating configuration is not very efficient, as the maximum heating zone for the tape is located at the knee of the guide instead at the nip-point between the tape and the roller. After this knee-region, the tape cools rapidly on around 30 mm, before reaching this nip-point.



(a)



(b)

Figure 4: (a) Visualization of the beam rays in a laser simulation; (b) management of the sliding heating boundary condition in the explicit thermo-mechanical simulation.

3. Conclusions

In this paper, a two steps approach has been proposed to simulate the ATP process with an explicit 3D thermo-mechanical analysis. The first step is a laser simulation based on a ray tracing model to assess the heating flux imposed by the laser on the parts. Then these heating boundary conditions are used in the ATP simulation itself in order to get the accurate temperature field history. This model has been modeled in a 3D frame, improving the usual 2D section models seen in literature.

Moreover, the explicit approach allows for more complexe tool kinematic management than for steady-state approach, while impacting negatively the CPU time. However, considering the present laser model, some additional work has still to be done to handle complexe tool kinematic as curviline path wihich is not circular. It should be the goal of future works.

Moreover, as shown in [4, 12] the laser/composite interaction exhibites a complex and highly anisotropic behaviour while it is only an isotropic specular approach for now. Again, it should be study in future works.

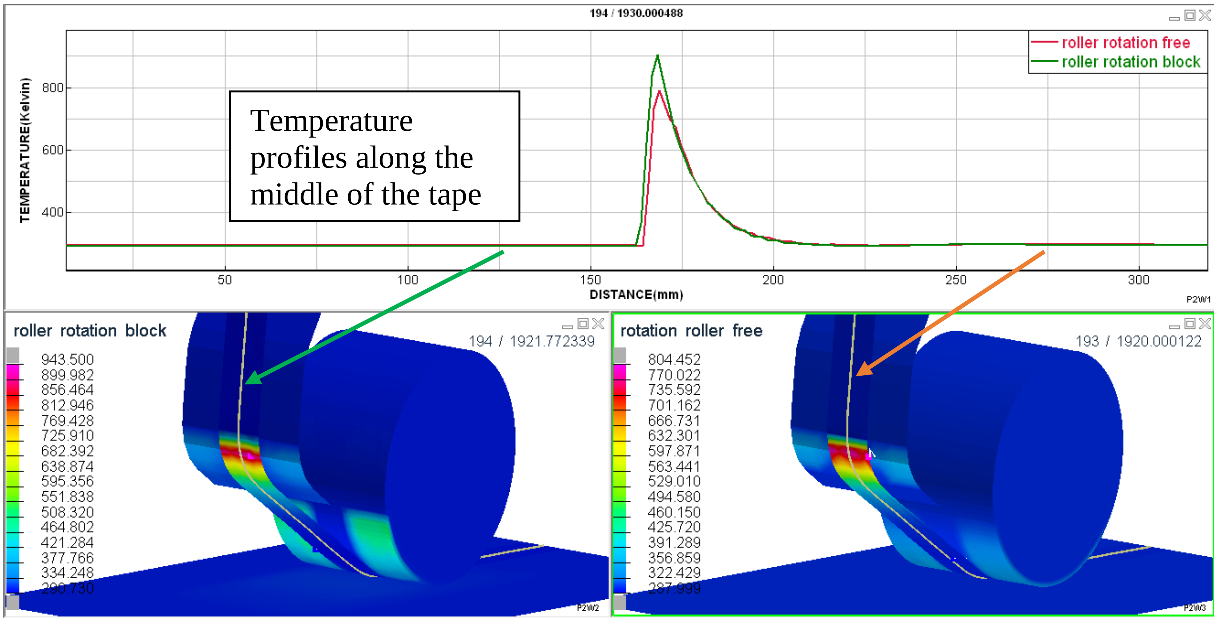


Figure 5: Temperature contour results obtained during the deposition of a tape – Explicit 3D thermo-mechanical model. (left) simulation with the rotation of the roller block; (right) with free rotation of the roller and friction between the roller vs the tape and the support; (top) temperature profile along the middle of the tape.

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References

Références

[1] R. Schledjewski et M. Latrille, «Processing of unidirectional fiber reinforced tapes – fundamentals on the way to a process simulation tool (ProSimFRT),» *Composites Science and Technology,* vol. 63, pp. 2111-2118, 2003.

[2] R. Schledjewski, «Thermoplastic tape placement process – in situ consolidation is reachable,» *Plastics, Rubber and Composites,* vol. 38, n°138, pp. 379-386, 2009.

[3] C. Nicodeau, "modelisation du soudage en continu de composites a matrice thermoplastique", Centre de Paris: Thèse, ENSAM, 20 septembre 2005.

[4] W. Grouve, "Weld strength of laser-assisted tape-placed thermoplastic composites", University of Twente, 2012.

[5] F. Yang et R. Pitchulani, «Nonisothermal healing and interlaminar bond strength evolution during thermoplastic matrix composites processing,» *Polym. Compos.,* vol. 24, pp. 263-78, 2003.

[6] P. P. Parlevliet, H. E. Bersee et A. Beukers, «Residual stresses in thermoplastic composites—A study of the literature—Part I: Formation of residual stresses,» *Composites Part A*, vol. 37, p. 1847–1857, 2006.

[7] M. Khan, P. Mitschang et R. Schledjewski, «Tracing the void content development and identification of its effecting parameters during in-situ consolidation of thermoplastic tape material,» *Polymer and Polymer Composites,* vol. 18, n°11, pp. 1-15, 2010.

[8] J. Tierney et J. W. Gillespie, «Modeling of Heat Transfer and Void Dynamics for the Thermoplastic Composite Tow-Placement Process,» *J. Compos. Mater.*, vol. 37, p. 1745–68, 2003.

[9] F. O. Sonmez et H. T. Hahn, «Modeling of Heat Transfer and Crystallization in Thermoplastic Composite Tape Placement Process,» *J. Thermoplast. Compos.,* vol. 10, pp. 198-240, 1997.

[10] J. J. Tierney et J. Gillespie, «Crystallization kinetics behavior of PEEK based composites exposed to high heating and cooling rates,» *Composites Part A,* vol. 35, p. 547–558, 2004.

[11] M. Khan, P. Mitschang et R. Schledjewski, «Identification of some optimal process parameters to achieve higher laminate quality through tape placement,» *Advances in Polymer Technology,* vol. 29, n°12, pp. 98-111, 2010.

[12] C. Stokes-Griffin et P. Compston, «Optical characterisation and modelling for oblique near-infrared laser heating of carbon fibre reinforced thermoplastic composites,» *Optics and Lasers Eng.,* vol. 72, pp. 1-11, 2015.

[13] M. Khan, P. Mitschang et R. Schledjewski, «Parametric study on processing parameters and resulting part quality through thermoplastic tape placement process,» *Journal of Composite Materials,* vol. 47, n°14, pp. 485-499, 2003.

[14] M. Narnhofer, R. Schledjewski et P. Mitschang, «Simulation of the tape-laying process for thermoplastic matrix composites,» *Advances in Polymer Technology*, vol. 32, pp. 705-713, 2013.

[15] J. Bergheau, V. Robin et F. Boitout, «Finite Element Simulation of Processes Involving Moving Heat Sources. Application to Welding and Surface Treatment.,» *Journal of Shanghai Jiaotong University (Science)*, vol. 5, n°11, pp. 114-122, 2000.

[16] Y. Duplessis Kergomard, M. Perrin, A. Trameçon et P. De Luca, «hybrid thermoplastic yarn to 3d complex shaped thermoplastic composite structure: simulation of braiding and subsequent consolidation», *ECCM16,* Sevillia, 2014.

[17] ESI GROUP, PAM-FORM 2G 2015 User's Guide, ESI GROUP, 2015.

[18] Y. Duplessis Kergomard, B. Satheesh, L. Dufort et R. Schledjewski, «3D thermo-mechanical model based simulation of the welding of thermoplastic composite tape using automated tape laying (ATL) process», *ICCM20,* Copenhagen, 2015.

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