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# Contribution of thermo-mechanical parameters and friction to the bonding of thermoplastic tapes in the tape winding process

Mikhael Tannous[a,∗], Anaïs Barasinski[a], Christophe Binetruy[a], Benoît Courtemanche[b]

[a] GéM, Ecole Centrale de Nantes, France
[b] CETIM, Ingénierie Polymères & Composites, France

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ABSTRACT

Ensuring a good inter-laminar bonding while accelerating the production in the tape winding process of thermoplastic tapes is a key question. Finite element models and numerical simulation help to predict the influence of process parameters on the product quality. This article addresses the finite element modeling of the thermal and mechanical phenomena involved in the tape winding process of thermoplastic tapes. It highlights through simulation and experimental validations the influence and necessity to promote the friction between the different components on the product quality and the process itself. This parameter is neglected in the literature which focuses mainly on thermal parameters and occasionally on the mechanical parameters (roller deformations, etc.), excluding the friction.



## 1. Introduction

Tape winding has an increasing value because it reduces the cost of manufacturing composite structures while preserving a high quality as indicated by Sun et al. (1995) and eliminating the autoclave needs as claimed by Barasinski et al. (2011). Advances in robotics and manipulators design made the tape winding process affordable even to small companies as mentioned by Koussios et al. (2012). Tape winding technology is in continuous progress and is optimized such a way that production is faster and the product quality is enhanced as insisted by Schmitt and Witte (2012). The common physical mechanism to all thermoplastic composite processes is the fusion bonding that is responsible for the cohesion between yarns and plies and is the main factor that leads to a good product quality as described by Schell et al. (2009). The fusion bonding, first of all, is a thermal mechanism extensively studied in the literature because the laser assisted filament winding technology started with the fiber placement technology and consisted to heat two layers of thermoplastic tapes and put them into contact. In absence of roller pressure, or tape tension, obtaining a good inter-laminar bonding reduces to a thermal problem. Therefore, the heating source was a major concern in the literature. Modeling the process required an appropriate modeling of the heating source. There are many technologies available: Gennaro et al. (2011) used an infrared heating source, Toso et al. (2004) used a Hot Gas Torch, Stavrov and Bersee (2005) used an electromagnetic radiation and more precisely a resistance welding, while Ageorges et al. (2001) used friction as a heating source. Other heating sources exist and are listed by Shih (1997): thermal conduction from an external source such as contact with hot platens, microwave, radiofrequency, or laser (see Wang and Lou (2003) for example). The laser heating was first discussed in Beyeler and Güçeri (1988) and later adapted by Mazumdar and Hoa (1993). Laser-assisted fiber placement machines were enhanced for mass production and for large industrial products such as submarine structures studied by Sharp et al. (1995), and is nowadays frequently used in the fusion bonding process of thermoplastic composites as done in Casalino and Ghorbel (2008). The interface temperature prediction was the main key to get a correct model of the process, and controlling this temperature became a strong objective: Tierney and Gillespie (2006) used a closed loop control system to control the temperature of the interface between the top deposited tape and the substrate in order to achieve a good inter-laminar bonding quality.

However, the interface temperature could not be precisely predicted without accurately modeling the interply contact resistance. The thermal conductance between two contacting bodies was introduced a few decades ago. Cooper et al. (1968) is among the first works in the literature to address this issue, which made thereafter the subject of many research works that aimed to describe it theoretically and find an appropriate physical law as done by Mikic

∗ Corresponding author.
*E-mail address:* mikhael.tannous@ec-nantes.fr (M. Tannous).

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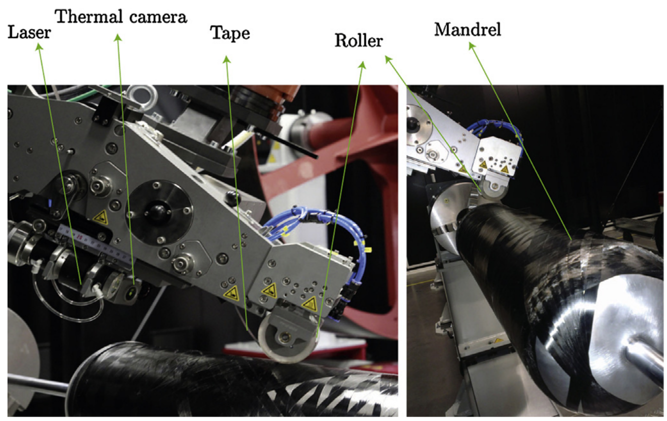


**Fig. 1.** Laser assisted tape winding machine (AFPT).

(1972). Nowadays, interply thermal contact resistance is still investigated in the simulation and studies of the tape winding process or the tape placement technology. In fact, interply thermal contact resistance was the main concern in Barasinski et al. (2013) for the study of an automated tape placement process.

With the introduction of the roller to the fiber placement technology, the roller pressure and the distribution of the pressure became mechanical parameters that influence the bonding quality. Rigid rollers were replaced by deformable ones for a better pressure distribution. The effect of pressure on the welding of two composites ribbon was addressed by Hinkley et al. (1997) then the bonding became a thermo-mechanical problem. The bonding is achieved when a sufficient pressure is applied on two bonding tapes having reached a given temperature for a sufficient period of time. Achieving a good inter-laminar bonding quality with the lowest temperature, pressure and exposure time were the main concern in Schell et al. (2009). The only mechanical parameter that contributes to the good bonding quality is the roller pressure and distribution. Therefore, deformable rollers allow a better pressure distribution.

The influence of rotation and tape tension to the bonding quality should be considered. There are very few papers on the effect of tape tension and winding kinematics on the bonding quality. The consolidation pressure and winding speed for carbon thermoplastic composite were studied by Colton and Leach (1992). It was found that high speed and consolidation pressure reduced void in the product and thus enhanced the inter-laminar bonding quality. However, the literature still focuses on the thermal problem as the main key behind the interply defaults and the bad bonding that occurs during the process.

This article deals with the laser-assisted winding of carbon thermoplastic tapes on a technologically advanced machine (see Fig. 1) where the manufacturing process combines several mechanical, kinematic and thermal parameters. It presents a thermo-mechanical model in which all mechanical, kinematic and thermal parameters are taken into account in order to evaluate the quality of the adhesion between the deposited tapes. The friction between the different components, and especially the roller/tape and roller/mandrel friction are taken into account. Note that the friction is considered as a pure mechanical parameter. The heat generated by the friction in this study case, and for the considered machine leads to a negligible temperature increase. Therefore, the friction is not a thermal parameter as in Ageorges et al. (2001), where friction is the heating source. Controlling pure mechanical parameters and especially the friction for a better inter-laminar bonding is, to the best of our knowledge, not adressed in the literature. Studies today focus on the roller's behavior and deformation, which affect the pressure distribution, and thus the literature neglects the friction role.

This research work highlights via simulation and experimental studies the importance of the friction.

The proposed approach relies on commercial finite element software (Abaqus) and can be implemented by engineers with a reasonable computational cost. Note that the computational effort could be decreased by taking advantage of model reduction methods such as the PGD (Proper Generalized Decomposition) for solving the thermo-mechanical problem in Chinesta et al. (2014).

This article aims at highlighting the contribution of mechanical parameters and more specifically, friction coefficients between the roller, tape, and mandrel, on the inter-laminar bonding quality. For that reason, no results concerning the thermal problem will be shown. This later has been extensively addressed in the literature.

The article is structured as follow. The process is described in a first part. Secondly, the production limits and defaults due to neglecting the friction are presented. Then, the role and importance of friction are assessed through experiments before developing a thermo-mechanical finite element model to have a better understanding of the process and to predict the bonding quality with respect to the different thermal, kinematic and mechanical parameters. Some conclusions are drawn. Future applications based on the results of this research work are proposed.

## 2. The process and its different parameters

Fig. 1 shows the tape winding machine (Advanced Fiber Placement Technology (AFPT)) used in this study. It is a robotized tape winding machine that consists of a rotating mandrel on which thermoplastic tapes are placed by the robot. On the left hand side of Fig. 1, the tapes are placed such a way they form a 45° angle with respect to the rotation axis, while on the right hand side of Fig. 1 the tapes are placed at a 90° angle (circumferential winding). The main applications and illustrations of this article focus on the circumferential winding.

The tapes are placed a pressure given by a roller and are subjected to a controlled tension. A laser source is used to heat the tapes up and the temperature is controlled by an infrared camera. Fig. 3 illustrates a 90° filament winding process. Although the application examples of this article concern mostly a cylindrical mandrel of $R_{mandrel} = 100.5$ mm, the mandrel can have several forms and diameters. Larger diameters are also of interest. The linear placement velocity can vary in the [3, 30] m/min interval which is equivalent to a [0.5, 5] rd/s rotational velocity on the 100.5 mm mandrel radius. Polyamide thermoplastic tapes (Celstran CFR-TP PA6 CF60-01) are considered, with carbon fiber occupying 60% of the tapes mass and 48 % of the tapes volume. The tapes are 1.2 mm wide and $\epsilon = 0.19$ mm thick and have the orthotropic characteristics reported in Tables 1 and 2. Note that 1 indicates the carbon fiber direction, 2 and 3 correspond to the two other directions orthogonal to 1.

The tape is under tension and has an attack angle $\alpha_{tape} = 45°$. The tape tension is ensured via a braking motor that imposes a force opposite to the tape's motion and depends on the winding velocity. It can be up to 300 N. The pressure in the roller's actuators can range from 0.1 MPa to 0.6 MPa. The roller itself is removable and can be rigid (metal roller) or deformable (silicone roller). One can also change the roller's dimensions. However, the one used in this study has a 40 mm external radius, a 20 mm internal radius and a 20 mm width. The roller pressure can cause large deformation to the silicone one. The later is used in this study. The silicone is an isotropic material and has the characteristics listed in Table 3. An experimental test aiming at determining the Young Modulus of the silicone roller is performed on the latter and the results are shown in Fig. 2. It is obvious that the silicone has a non linear behavior for $\epsilon \geq 0.3$. However, during the winding process, the roller deformation does