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# EXPERIMENTAL BENCH FOR THE DETERMINATION OF THE THERMAL CONTACT RESISTANCE BETWEEN TAPES IN THE AFP PROCESS

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## Abstract

A specific experimental set up was developed in order to evaluate the heat transfer occurring within a laminate of pre-impregnated tapes according to their level of consolidation when irradiated with a laser source. The apparatus was designed to reproduce and control Automated Fiber Placement (AFP) process conditions such as power of infrared laser, contact pressure as applied by the silicon roller, and temperature of heated lay-up table.

Analysis of surface temperature and transmitted heat flux through a single or a two-tapes assembly allowed to evaluate the evolution of thermal contact resistances with contact pressure.

## 1. Introduction

Understanding how heat is absorbed and transmitted in the material is a key point for controlling the thermal history of a laminate being layed-up with the AFP process. First of all, the interaction between the composite tape and the incoming laser radiation must be addressed [1–3]. Laser incidence, fibre orientation and lay-up velocity have long been identified as key factors influencing the laser absorption by the composite and its increase in temperature [4-5].

Secondly, the composite is mostly represented from a mesoscale stand point where its thermal properties are assumed to be homogenous. The medium is pictured as a homogenized bulk and potential artefacts at the interface are discarded. Investigating heat transfer from a micro scale perspective is the next step to enhance the understanding of the thermal phenomena occurring in the AFP process [6]. In particular, it is known that at this very short time scale, heat transfer within the laminate volume and the subsequent quality of the part is highly sensitive to the intimate contact and thermal contact resistances between layers [7]. The quality of contact at these interfaces depends on the material temperature as well as contact pressure and time [8].

Measuring thermal contact resistances during the manufacturing of the part can only be achieved through the on-line monitoring of surface temperature which has long proven difficult [9]. Indeed, this operation, generally achieved with the help of infrared cameras, is made uneasy by the minimal space available in the vicinity of the lay-up head and by the rapid motion of the system.

In this article, an original approach was taken to address this technical matter: designing a static experimental set-up meant to recreate in laboratory the AFP heating condition being very short laser irradiations and contact pressure through the compaction of a silicon roller. In particular, this specific bench was developed in order to address the problematic linked to the heating of CFRP tapes: analysing the influence of laser power, incidence angle and fiber orientation on the tape / laser interaction, and studying the influence of contact quality between tapes on heat transfer.

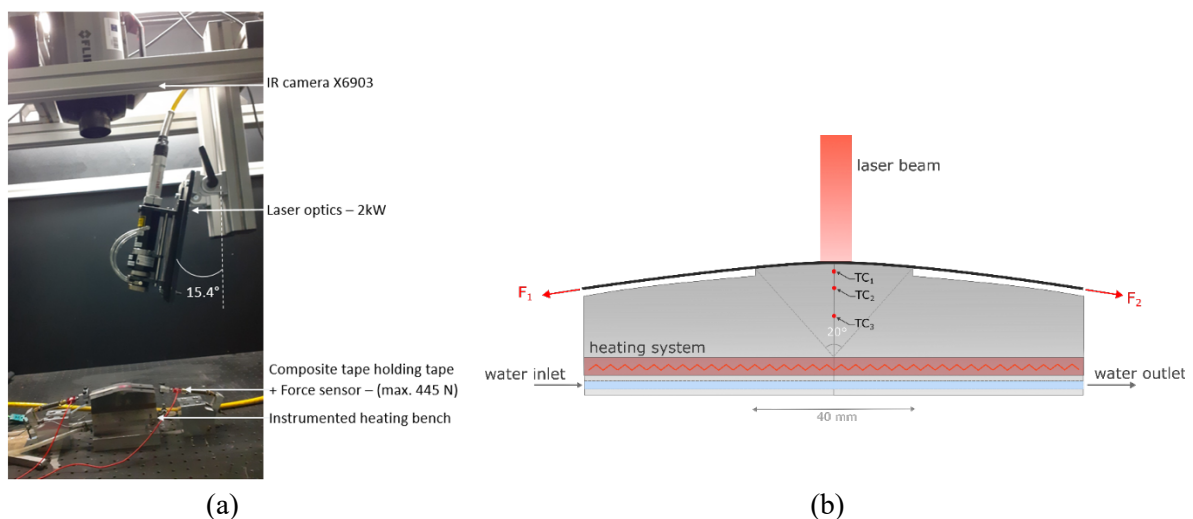
This work presented in the following focuses on the second feature of the bench.

## 2. Experimental set up specifications

The core of the set-up is a metallic heated metallic bench on which laser diode is mounted. A composite tape can be held onto the metallic support and irradiated by an inclinable 2kW laser diode with controlled time and power. The tape is held with the help by two flanges on its opposite sides. Each flange is mounted on a specific traction system which allows to apply increasing controlled tension, and as a consequence increasing contact pressure, on the tape. Tension forces are measured with two 500N force sensors (Futek, LSB2021).

A schematic view of the bench is presented below. A curved surface of opening angle  $20^\circ$  and radius of curvature 115mm is machined over 40mm of the top surface of the bench to facilitate the contact with the tape and also to control finely contact pressure over this area. The calibrated contact pressure ranges from 0.35bars to 1.90bars ( $\pm 0.01$ bars) which is relevant with the pressure applied by the compaction roller in the AFP process.

The bench itself is equipped with a heating resistive wire and instrumented with three  $25\mu\text{m}$  diameter K-type thermocouples, composing a short response time heat flux sensor. Above the support an IR camera (FLIR XC609) monitors the evolution of temperature at the composite surface.



**Figure 1.** (a) experimental set-up (b) schematic view of the measurement principle

## 3. Heat transfer through a layed-up laminate in solide state

The objective of this section is to evaluate the effect of increasing surface contact on the heat transfer within a composite laminate irradiated with the laser diode. Firstly, thermal contact resistances between the laminate and the metallic bench are measured by performing irradiations on a single tape. Secondly, the sensivity of heat transfer in a two layers laminate is assessed according to the level of consolidation – partially or fully consolidated.

### 3.1. Measurement on a single tape

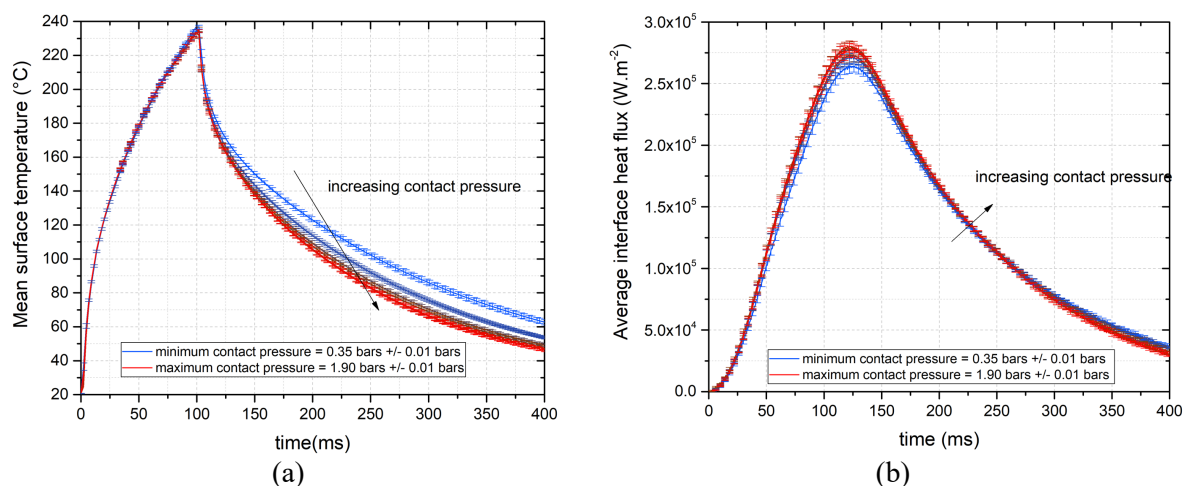
The tape is first installed on the bench with minimum contact pressure (0.35 bars +/-0.01 bars). The tape surface is irradiated for 100 ms at 5 % of the laser power ( $0.64 \text{ MW.m}^{-2}$ ). The irradiation time was chosen so that the measured surface temperature is sensitive to the quality of contact on its rear-side interface during heating and cooling. The laser power was selected so that the temperature within the tape remains well below the polymer melting temperature and all interfaces remain in solid-state.

After the first laser shot, pressure is increased by 0.30 bars and the tape is irradiated again. This sequence is repeated up to the maximum pressure (1.90 bars +/-0.01 bars).

Figure 2 (a) and (b) present respectively the evolution of surface temperature measured with the camera and of heat flux measured by the heat flux sensor. Results are averaged over five samples.

We can observe in Figure 2 that the surface temperature is slightly sensitive to the increase in pressure during the heating stage as the maximum reached at 100ms decreases by  $2^\circ\text{C}$ . But the most noticeable effect can be observed after the irradiation stage as the cooling rate increases greatly with the increase in contact pressure. Similarly, the heat flux recorded by the heat flux sensor implemented in the metallic bench increases with pressure proving a greater heat diffusion at the interface.

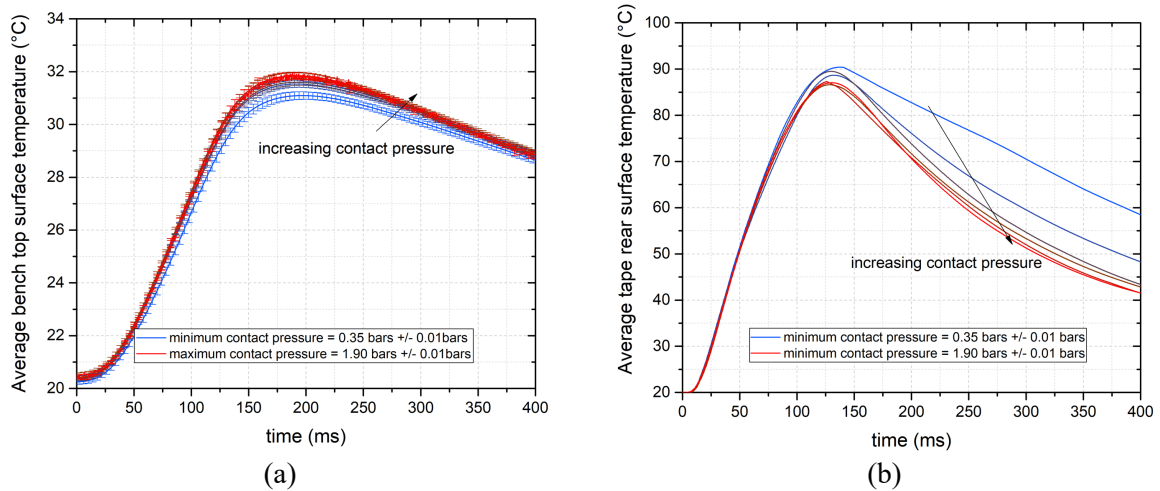
These observations show that the thermal contact resistance at the interface decreases with increasing pressure and that the metrology implemented in the experimental bench is sensitive to its evolution.



**Figure 2.** Evolution of (a) surface tape temperature and (b) transmitted heat flux  $\varphi$  with time and contact pressure

Figure 3(a) shows in particular temperature at the bench top surface estimated with the help of the heat flux sensor. The sensitivity to heat diffusion only occurs after 25 ms due to the diffusion time constant of the composite layer [6]. After 25 ms, the support temperature rises with, as before, a magnitude dependant of the contact pressure.

With the help of the microscale thermal model developed in [6], the bottom temperature of the tape evolution during the laser heating can be calculated (Figure 3(b)). To do so, surface temperature (Fig. 2a) and the interface heat flux (Fig. 2b) are imposed as boundary conditions in the thermal model.



**Figure 3.** Evolution of (a) bench surface temperature ( $T_2$ ) and (b) tape rear surface temperature ( $T_1$ ) with time and contact pressure

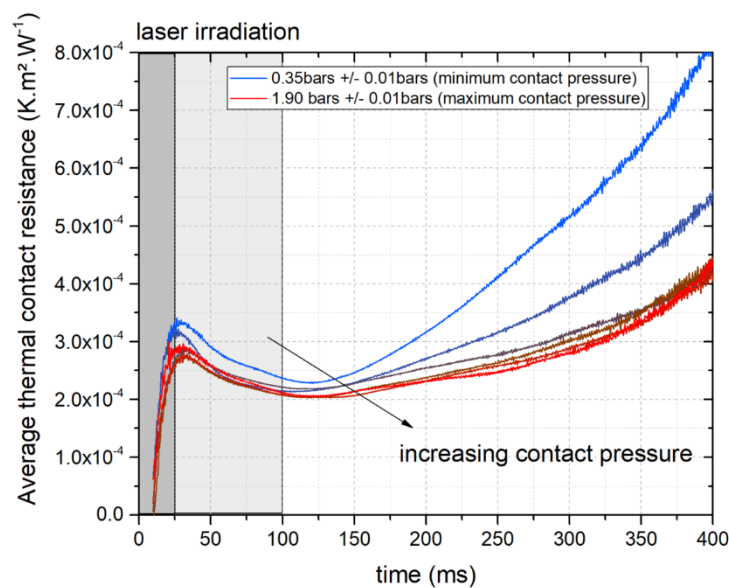
Finally, an average thermal contact resistance can be calculated with the expression:

$$RTC = \frac{T_1 - T_2}{\varphi}$$

Where  $T_1$  and  $T_2$  are the temperature from each end of the interface, here in the composite (fig 3b) and in the bench (fig 3a), and  $\varphi$  the heat flux crossing the interface (fig 2b).

The calculated thermal contact resistance (RTC) evolution with time is depicted in Figure 4. As heat diffusion is very low below 25 ms, data should not be considered in that time range. Between 25ms and 100ms, the thermal contact resistance is comprised between  $2.5 \cdot 10^{-4} \text{ K.m}^2.\text{W}^{-1}$  and  $3.1 \cdot 10^{-4} \text{ K.m}^2.\text{W}^{-1}$  which is relevant with the contact between two smooth surfaces.

A mere effect of pressure is visible below 1bar. After the heating stage, while one would have expected the measured values to asymptot, RTC values tend to increase in particular for the lowest contact pressure. This observation should be analysed with care as it could be induced by local modifications of the topology at the interface induced the the release of mechanical constraints.

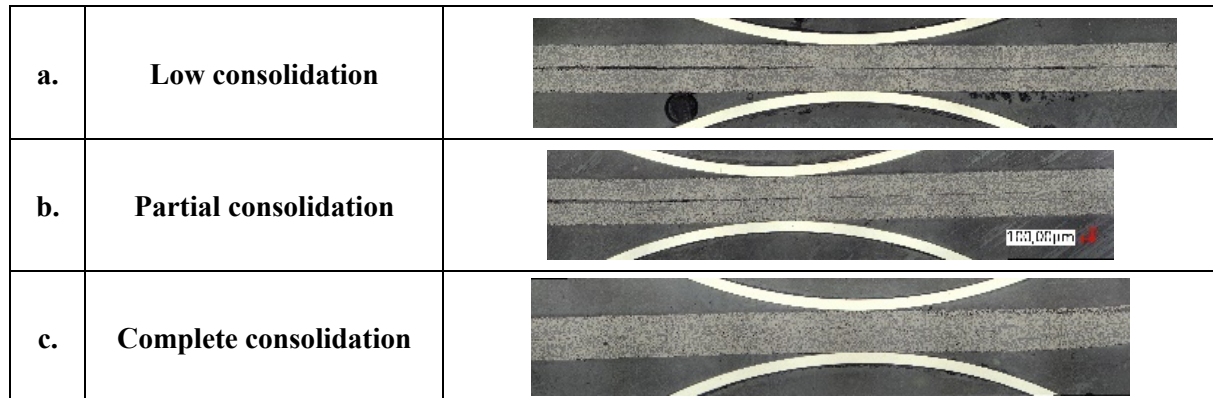


**Figure 4.** Evolution of average thermal contact resistance with time and contact pressure

Further work should include a confrontation between the experimental results and a refined contact model of the interface.

### 3.2. Measurements on a two tapes assembly

A set of assemblies of two tapes was manufactured by Coriolis Composites in controlled operating conditions. Three different levels of consolidation were processed by varying the lay up speed, supporting table temperature and target temperature. Micrographs of the three types of laminates are displayed in Figure 5.



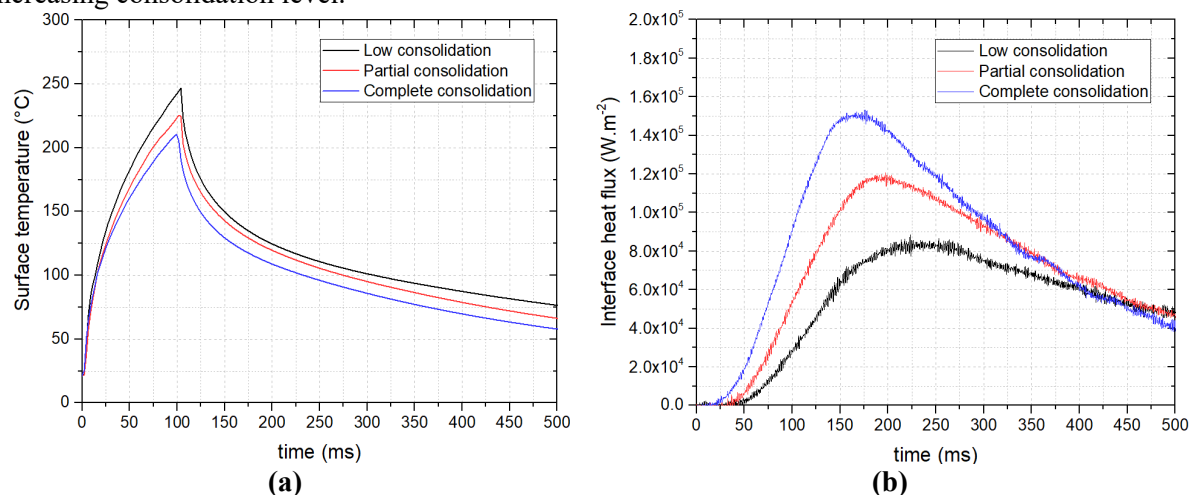
**Figure 5.** Evolution of interface microstructure according to the level of consolidation (low (a), partial (b) or complete (c)).

All three types of assembly were tested on the experimental bench in the following conditions:

- Incoming heat flux: 5% of the laser power ( $0.64 \text{ MW}\cdot\text{m}^{-2}$ )
- Heating time: 100ms
- Contact pressure: 1.60 bars

It is chosen to work at the maximum available contact pressure since the sensitivity to its magnitude only appears for the lowest side of the range.

Figure 6 displays the evolution of surface temperature and heat flux with time according to the three levels of consolidation. We can notice that the measurements are sensitive to the quality of consolidation of the interface. Firstly, the maximum surface temperature reached at the end of heating decreases for increasing consolidation level.



**Figure 6.** Evolution of (a) surface temperature and (b) transmitted heat flux according to the level of consolidation

As it is known from the previous tests that the diffusion time within the thickness is lower than 100ms, this decrease highlights the improved heat transfer in the most consolidated laminate. Consequently, heat flux at the interface increases for enhanced consolidation level and hence for lower thermal contact resistance at the tapes interface.

### 3. Conclusions

An experimental set-up was designed and developed in order to study heat transfer in single tape and laminates during the heating stage of the AFP process. The following experimental campaigns allowed to successfully:

- Recreate static heating conditions representative of the process (high intensity short pulses, heating table, controlled pressure).
- Study thermal contacts at the interfaces between tapes and between a tape and its metallic support.

In particular, this work was supported by original experimental development such as high sensitivity heat flux sensors and as well as high speed cameras that allowed to measure heat transfer during very short timescale.

The analysis of the recorded signals highlighted the sensitivity of the measurements to all parameters of interest identified prior to the study: quality of contact at interfaces

Future work will address the possibility of in-situ consolidation with the static bench of an assembly. In particular, primary empirical investigations have shown weak but present bonding of initially unconsolidated assemblies through incremental welding. Further development of the experimental protocol requires the implementation of an adequate thermal model to identify and optimize the suitable heating conditions.

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### References

- [1] C.M. Stokes-Griffin and P. Compston. A combined optical-thermal model for near-infrared laser heating of thermoplastic composites in an automated tape placement. *Composite Part A*. (75) 104-105, 2015.
- [2] V. Le Louët and al. Directional spectral reflectivity measurements of a carbon fibre reinforced composite up to 450°C. *International Journal of Heat and Mass Transfer* (112) 882-890, 2017.
- [3] A. Zaami and al. Optical characterization of fiber-reinforced thermoplastic tapes for laser-based composite manufacturing, *Composites Part A*. (146) 106402, 2021.
- [4] WJB Groupe. *Weld strength of laser-assisted tape places thermoplastic composite [Ph.D]*, Enschede, the Netherlands: University of Twente, 2012.
- [5] C.M. Stokes-Griffin and P. Compston. An inverse model for optimization of laser heat flux distributions in an automated laser tape placement process for carbon fibre-/PEEK. *Composite Part A*. (88) 190-197, 2016.
- [6] A. Le Reun and al. Numerical simulation at the micro-scale for the heat transfer in the thermoplastic composites laser-assisted AFP process. *Composite Part A*. (179) 108010, 2024
- [7] A. Levy and al. Inter-layer contact resistance evolution with the degree of intimate contact in the process of thermoplastic composite laminates. *Journal of Composite Materials* (48) 491-503, 2014.
- [8] A. Barasinski and al. Identification of non uniform thermal contact resistance in automated tape placement process. *International Journal of Material Forming* 7 (4) 479-486, 2014.
- [9] S. Réquillé. Automated Fiber Placement of Thermoplastic Material: Towards an Innovative Way of Controlling Temperature Homogeneity, ITHEC 2022 Proceedings, 2022.