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Propagation du champ de température à l'échelle microscopique dans les composites renforcés de fibres de carbone unidirectionnelles à matrice thermoplastique

Microscale temperature field propagation in unidirectional carbon fibre reinforced thermoplastic composites

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Résumé

Etant donnée la constante demande d'amélioration des procédures et des performances dans l'industrie des composites, il est crucial de comprendre le comportement thermique des composites thermoplastiques renforcés de fibres de carbone (CFRTP). Bien que les phases individuelles de ces matériaux aient des réponses très différentes aux faisceaux incidents, le comportement thermique des composites est souvent étudié à l'aide d'un modèle de matériaux homogène équivalent. Dans cette étude, nous visons à éviter ces simplifications et à capturer leur hétérogénéité inhérente. L'étude de la propagation du champ de température est réalisée à une échelle microscopique afin de prendre en compte l'influence de facteurs tels que les porosités et la distribution des fibres. Des mesures expérimentales à l'aide d'une caméra thermique sont utilisées pour capturer l'évolution de la température à la surface d'une bande CFRTP unidirectionnelle chauffée par une lampe infrarouge (IR). Des simulations numériques sur la section transversale de la bande sont utilisées pour examiner l'évolution de la température à travers son épaisseur.

Abstract

With the constant demand for improved procedures and performance in the composite industry, understanding the thermal behavior of carbon fiber reinforced thermoplastic (CFRTP) composites becomes crucial. Even though the responses of the individual phases of these materials towards incident beams are very different, the thermal behavior of composites is often studied using homogeneous equivalent material models. In this research we aim to avoid such simplifications and capture their inherent heterogeneity. The study of the temperature field propagation is performed at a microscale intending to take into consideration the influence of factors such as voids and fiber distribution. Experimental measurements using a thermal camera are employed to capture the temperature evolution on the surface of a unidirectional CFRTP tape while heated by an infrared (IR) lamp. Numerical simulations on the tape's transversal section are employed to examine the temperature evolution through its thickness.

Mots Clés : Champ de Température, Microéchelle, Distribution des Fibres

Keywords : Temperature Field, Microscale, Fibre Distribution

1. Introduction

CFRTP composites can be recognized as a group of advanced materials that exhibit outstanding mechanical properties, and offer a wide range of potential applications in various engineering fields, including aerospace, automotive, and sports equipment [1]. Besides, as the composite industry strives for more sustainable practices, the recyclability of thermoplastic composites becomes increasingly relevant [2], [3]. However, compared to thermoset composites, the processing and production of thermoplastic composites are still in the early stages of development and a better understanding of their properties will help to enhance the quality of these materials [4].

The heating step during the production of CFRTP composite parts plays a crucial role in achieving proper consolidation and desirable mechanical properties [5]. Efficient and controlled heating is essential to ensure adequate resin flow, fiber impregnation, proper consolidation and also increase production rates [6]. Consequently, there is significant interest in comprehending and optimizing the thermal response of CFRTP.

It is a common practice in composites studies to use homogeneous equivalent material models [7], [8], but these simplifications can lead to inaccurate predictions and suboptimal processing conditions [9]. In this study, we address this limitation by conducting an analysis of the thermal field propagation at a microscale. The microscale analysis enables us to take into account the influence of factors such as fiber distribution, porosities, surface roughness and thickness variation on the thermal behaviour of CFRTP.

To comprehensively study the thermal behaviour of CFRTP composites, we employ a combination of experimental measurements and numerical simulations.

2. Materials

The targeted materials are unidirectional PA based CFRTP composite tapes that are often used to fabricate components using automated fiber placement (AFP) and filament winding (FW) techniques using IR lamps, laser and gas torches as heating sources [10], [11], [12]. Three samples with different characteristics which are summarized in the following table were chosen for this study.

	Tape 1	Tape 2	Tape 3
Width	12 [mm]	5 [mm]	50 [mm]
Fiber/matrix content	Low	Intermediate	High
Surface	Rough	Smooth	Rough

Tab. 1. UD CFRTP samples.

The thermal properties of the constituent materials used in the model are listed in the table below.

Materials	Fibers	Matrix
Density [kg/m ³]	1960	1290
Conductivity [W/mC]	0.43 (transversal)	0.27
Specific heat [J/KgK]	1296	1020

Tab. 2. Materials properties

3. Methods

To obtain the experimental data, a customized setup was designed to perform temperature measurements. The assembly consisted on placing the samples on a support and heating one of their faces with an IR lamp of 1000 W which intensity was adjusted with a power regulator device connected to a thermocouple. Target temperatures to be measured by the thermocouple were in the range of 20-70°C. To measure the surface temperature of the sample a high resolution thermal camera (FLIR A700) was employed, measurements were done in the sample's surface that was receiving the incident beams and also in the back face of the sample. Refer to Fig. 1 for illustration. Measurements were taken for values going from 5 to 120 seconds for heating and from 5 to 200 seconds for cooling.

The experimental setup offered the flexibility to adjust several geometrical parameters within specific ranges. These parameters included the sample-camera distance, which was set between 30 and 40 cm, the sample-source distance, set between 30 to 50 cm, the camera incidence angle varying from 90 to 120°, and the lamp incidence angle which remained fixed on 90°.

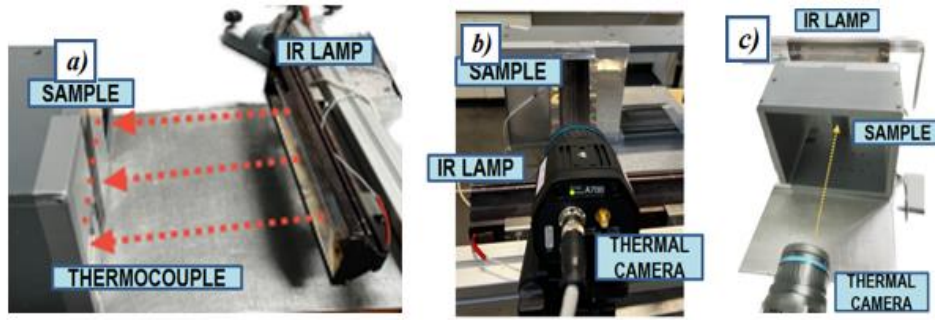


Fig. 1. Setup for temperature measurements a) Incident beams. b) Front face measurements. c) Back face measurements.

To determine the emissivity of each tape, the FLIR Research Studio program's emissivity calculator was employed. Emissivity values depend not only on the material properties but also on the specific geometrical parameters mentioned earlier, the IR source and the ambient conditions [13]. Considering that the range of the working geometrical parameters was small enough, the emissivity values were computed for a single combination of parameters and subsequently assumed to remain constant within the specified ranges. Values are presented in Tab. 3.

	Tape 1	Tape 2	Tape 3
Emissivity	0.83	0.81	0.87

Tab. 3. Emissivity values.

In addition to the experimental measurements, a 2D numerical model was developed using a combination of Matlab and Abaqus tools to investigate the temperature distribution within the tape's thickness. To take into consideration the heterogeneity of the material, micrographies of the sample's transversal section were analyzed to identify regions of interest that could represent different case studies in terms of fiber distribution. The size of the RVEs were squares from 180x180 μm up to 260x260 μm depending on the tape's thickness. An example is shown in Fig. 2.

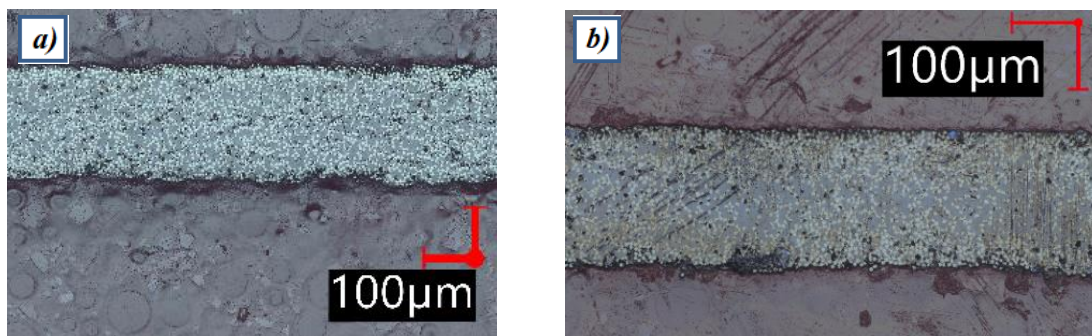


Fig. 2. Transversal section micrographs: a) Tape 2: Highly homogenous fibre distribution. b) Tape 3: Matrix-rich regions and fiber-rich regions can be distinguished.

For the simulations, the heat equation (Eq. 1) is solved by FEM under border conditions set to match the experimental measurement conditions but the values assigned to the individual properties of polymer and fibers were obtained from literature.

$$\rho c_p \partial T / \partial t = \nabla \cdot K \nabla T \quad (\text{Eq. 1})$$

Where ρ is the density, c_p the specific heat and K the conductivity for each material, T is the temperature and t the time. Other parameters were: ambient temperature=20°C, uniform heat flux on

top surface (0.008 W/mm^2), heat dissipation by air convection on top and bottom surfaces ($h=10\text{W/m}^2\text{K}$) and lateral surfaces were considered adiabatic.

4. Results and discussion

Regarding the obtained emissivity values, the tape with a smoother surface exhibited the lowest emissivity, while tape 3 with the higher roughness had the highest emissivity. This behaviour was expected because smooth surfaces reflect more of the incident radiation rather than absorbing and emitting it with respect to a rougher surface.

The conducted temperature measurements revealed a non-uniform temperature profile on the section of the tapes directly exposed to the IR beams (Fig. 3). This non-uniformity was particularly noticeable in tape 3 (Fig. 4a). However, when examining the absolute temperature values (Fig.4), it was observed that tape 2 (Fig.4b), the smoother tape, had higher temperatures compared to the rougher tape. This can be attributed to the smaller exposed area of tape 2, which made heat dissipation more difficult. Therefore, it is important to focus on the temperature gradient and the maximum difference between the lowest and highest values within the same tape, rather than the absolute temperature values themselves.

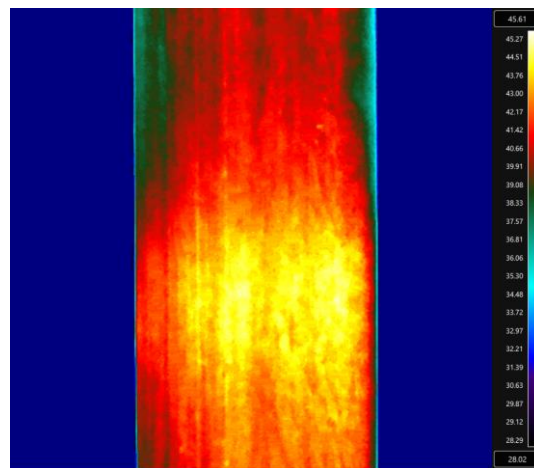


Fig. 3. Tape 3 Thermography.

Analysing the micrographies of each tape, it is noticeable that the fiber distribution in tape 2 is more uniform across its width compared to tape 3, which agrees with the fact that the temperature profile is more homogeneous on Tape 2 than on Tape 3. Additionally, when observing the measured temperatures on the back face of the tapes, a more uniform temperature profile is observed (Fig. 4c). This indicates that the temperature distribution within the tape had time to homogenize across its thickness.

In the simulations, various sections with different characteristics, were analysed to investigate the influence of parameters such as fiber distribution, porosities, and thickness variation on the thermal field evolution. Figure 5 demonstrates the temperature distribution in three different sections with the same material composition, results show significant temperature differences on the order of 50 degrees Celsius from one region to another for a constant top heat flux during 5 seconds. Fig. 5c exhibits the temperature distribution for a region numerically generated with a homogeneous fiber distribution, it can be observed that the temperature propagation is homogeneous and varies only in the y axis, this behaviour can be expected on a tape with an overall homogeneous fiber distribution as tape 2. These results are consistent with the experimental measurements where for the same exposure time a temperature difference of around 50 degrees Celsius was observed between different regions along the width of the tape.

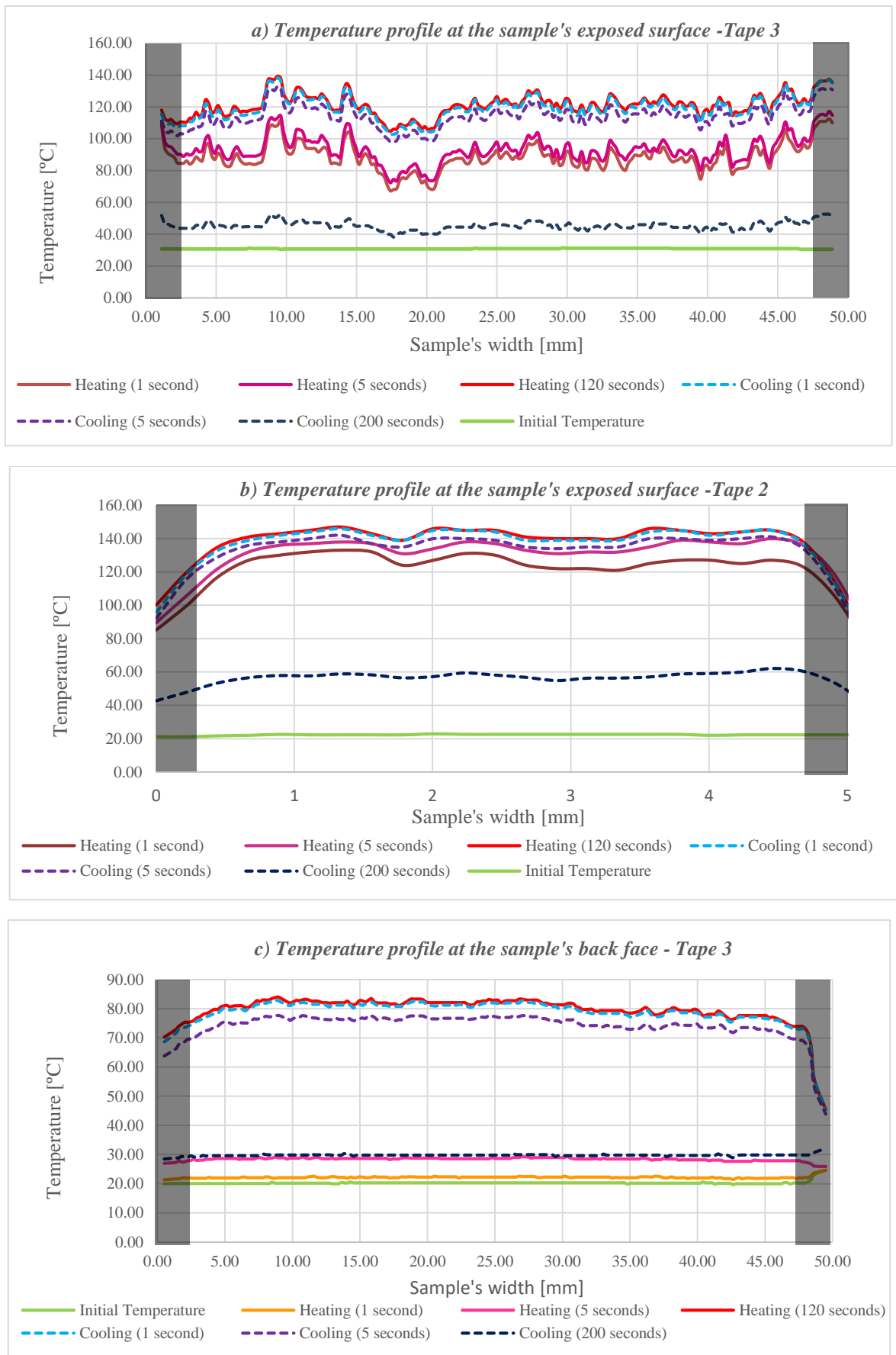


Fig. 4. Temperature profiles. Sections closer to lateral borders not considered due to edge effects.

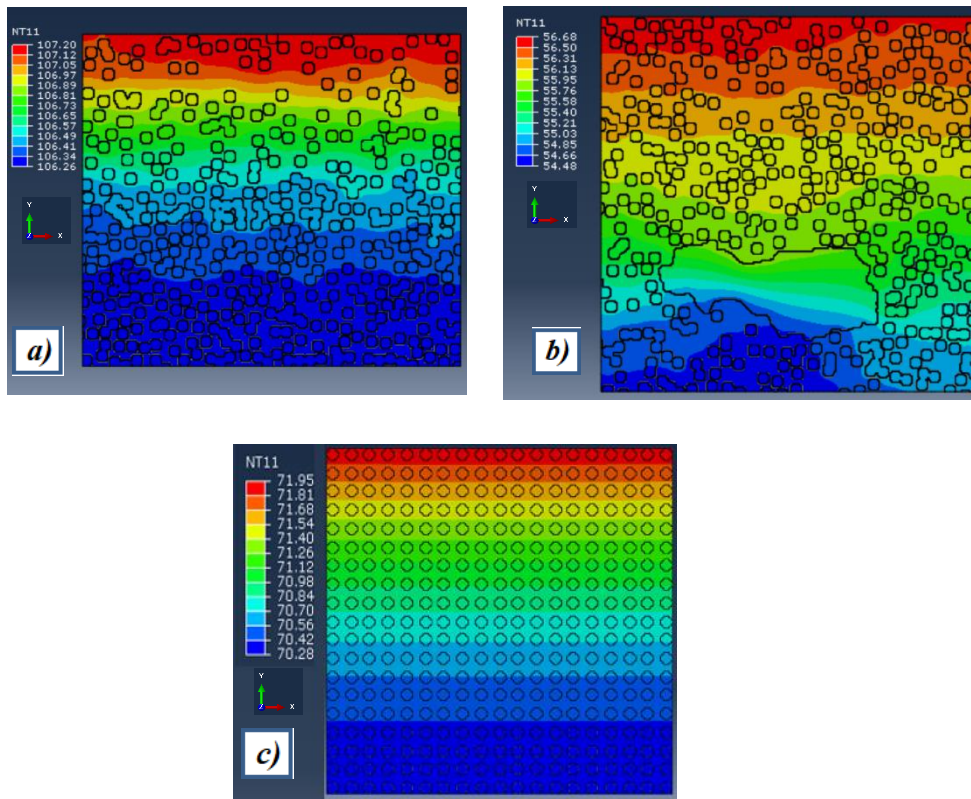


Fig. 5. Abaqus simulation of the temperature distribution [degrees Celsius] for different regions heated on top with a uniform heat flux during 5 seconds. a) High fiber quantity on the bottom, few fibers on top. b) Higher fiber quantity on top with a porosity near the bottom. c) Homogeneous fiber distribution section numerically generated.

5. Conclusion

In this study, the thermal behaviour of CFRTP composite tapes was investigated at a microscale, considering the influence of fiber distribution among other parameters. The experimental measurements using a thermal camera revealed a non-uniform temperature profile on the surface of the CFRTP tapes, with significant variations on the range of 67 to 117 degrees Celsius observed between different sections of the Tape 3. Numerical simulations also showed temperature differences on the order of 50 degrees Celsius (on the range of 56 to 107 degrees Celsius), between RVEs representing different regions along the tape's width. These findings emphasize the importance of considering local temperature gradients and heterogeneities in the analysis of CFRTP composites.

Overall, this research highlights the need to move beyond homogeneous equivalent material models and consider the inherent heterogeneity of CFRTP composites when studying their thermal behaviour. Nevertheless, it is necessary to point out the high computational cost of numerical analysis at the microscale as well as the limitations regarding the precision of experimental measurements. A solution to these constraints can be to combine these results with Artificial Intelligence for further analysis. In the scope of this research, this approach is addressed and the data obtained from both numerical simulations and experimental measurements, is being used to develop a data-driven model that captures the relationships between these heterogeneities and the thermal field propagation, enabling a deeper understanding of the underlying phenomena.

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