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Composite material thermal characterization for a digital twin-based model of an automated tape-laying process

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MATCOMP
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Gijón, June 2023

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Introduction

Automated Tape Laying Process

The Automated Tape Laying (ATL) Process uses prepregs to consolidate a structure

It is composed out of:

1. Material

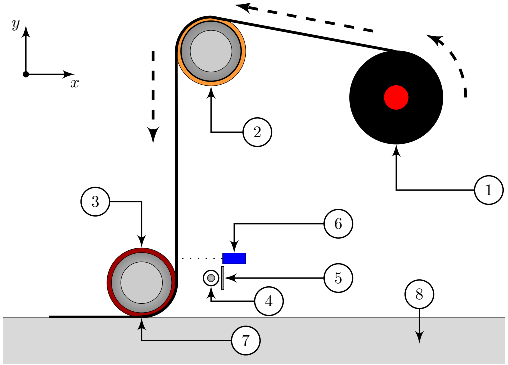

Figure 1. Process machine elements

Introduction
Automated Tape Laying Process

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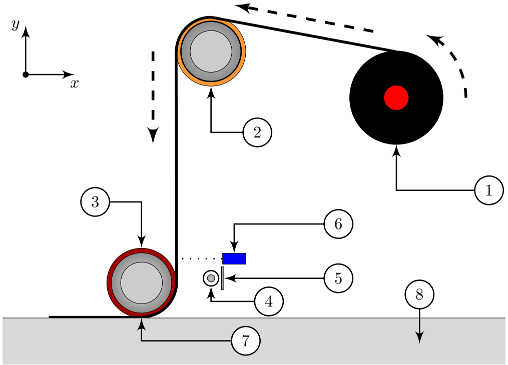
1. Material
2. Guide roll



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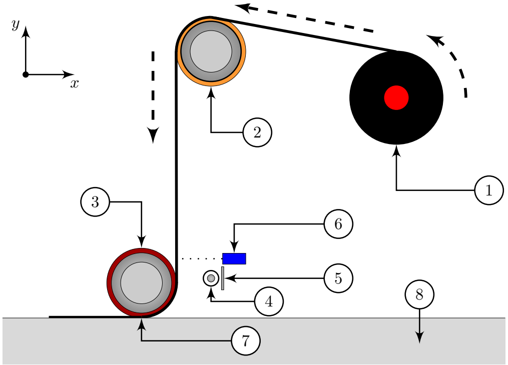

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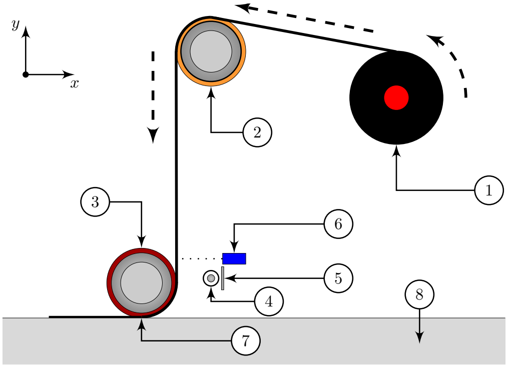
3. Compaction roll
4. Heating element



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The Automated Tape Laying (ATL) Process uses prepregs to consolidate a structure

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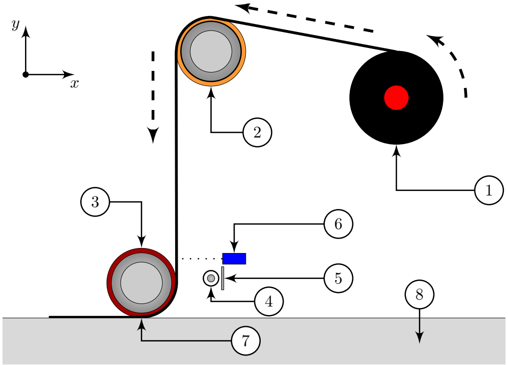
3. Compaction roll
4. Heating element
5. Reflector



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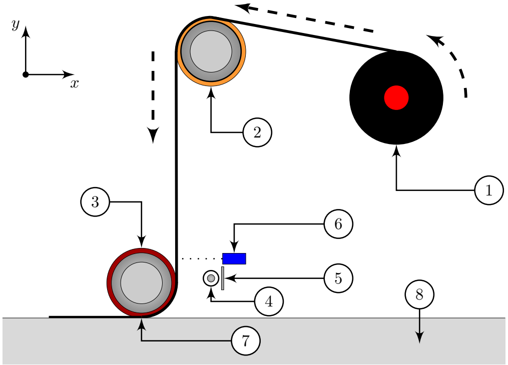
5. Reflector
6. Temperature sensor



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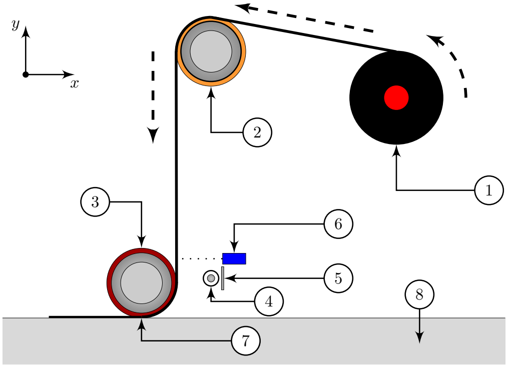
7. Nip point



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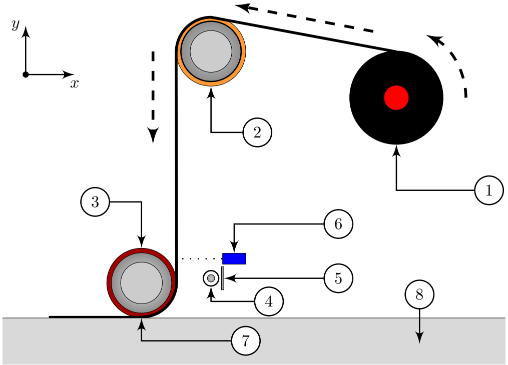
7. Nip point
8. Mould



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Introduction
Automated Tape Laying Process

The case of study is an ATL machine located at INEGI's laboratories, Porto, Portugal

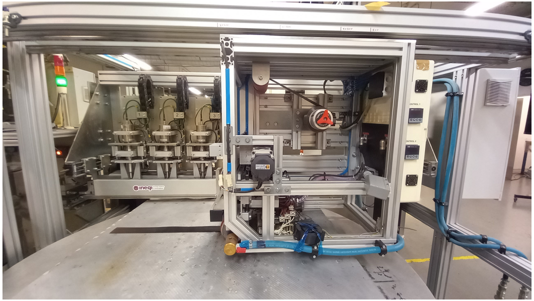

Figure 2. Real ATL process machine. Front view

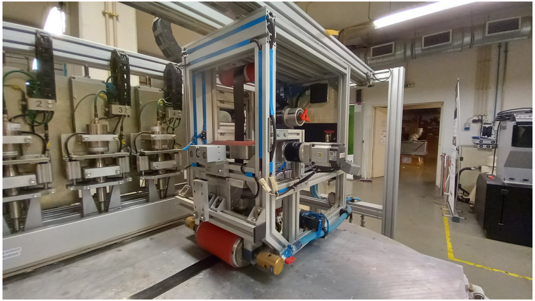

Figure 3. Real ATL process machine.

Introduction
Problem

- The relevant temperature is located at the **Nip Point**. Indicator 7 at Figure 4.

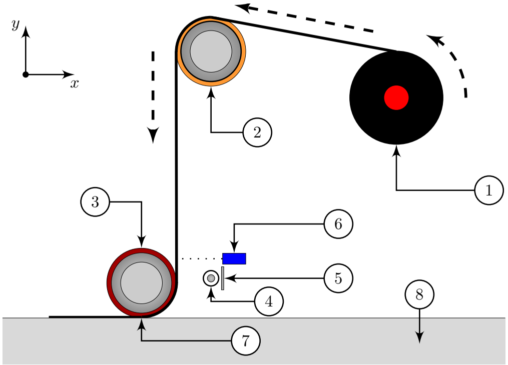

Figure 4. Process machine elements

Introduction
Problem

- The relevant temperature is located at the **Nip Point**. Indicator 7 at Figure 4.
- **No sensor** can be placed

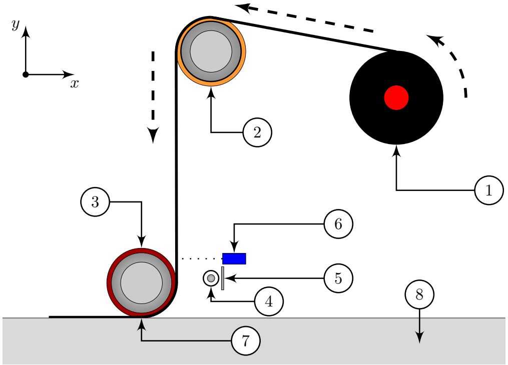

Figure 4. Process machine elements

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- The relevant temperature is located at the **Nip Point**. Indicator 7 at Figure 4.
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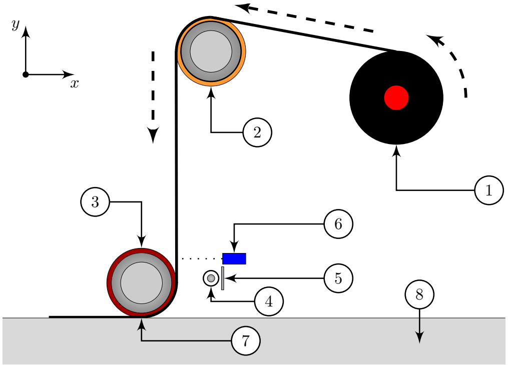

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- The relevant temperature is located at the **Nip Point**. Indicator 7 at Figure 4.
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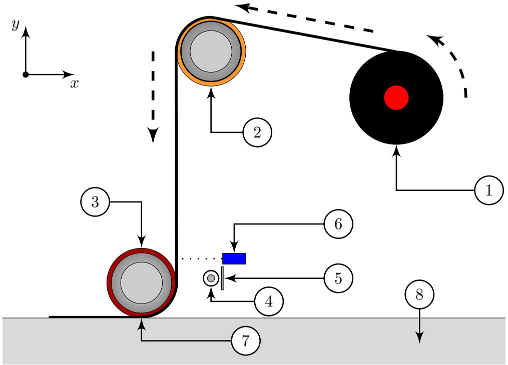
- A popper model needs to **replicate** the real process. *Digital Twin*



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Digital Twin

- The model **requires knowing the thermal properties as function of temperature** for the composite material:

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Digital Twin

- The model **requires knowing the thermal properties as function of temperature** for the composite material:
  - Thermal conductivity
  - Thermal-Optical properties
  - Specific heat

Introduction
Problem

Fundamental equation:

$$\frac{\partial}{\partial t}\int_{V_m}\rho_m\cdot cp(T_m)\cdot T_m dV_m=\int_{V_m} q''_{rad,m}\cdot dS_m+\int_{V_m} q''_{conv,m}\cdot dS_m+\int_{V_m} q''_{cond,m}\cdot dS_m$$
$$+\int_{V_m} k_m(T_m)\cdot(\nabla T_m\cdot\hat{n})\,dS_m-\int_{V_m}\rho_m\cdot cp_m(T_m)\cdot T_m\cdot(U\cdot\hat{n})\cdot dS_m \quad (1)$$

Radiation energy balance:

$$[J_{\lambda,j}]=[r_j]_{nx1}[G_{\lambda,j}]_{nxn}+[\tau_j]_{nx1}[G_{\lambda,j}]_{nxn}+[\varepsilon_j]_{nx1}[E_{\lambda,j}]_{nxn}$$
$$[G_{\lambda,j}]=\left([I]_{nxn}-[F]_{nxn}\left([r_j]_{nx1}+[\tau_j]_{nx1}\right)[F]_{nxn}[\varepsilon_j]_{nx1}[E_{\lambda,j}]_{nxn}\right)^{-1} \quad (2)$$
$$[q''_{rad,m}]=[J_{\lambda,j}]-[G_{\lambda,j}]$$

Introduction

Objectives

- Estimate the **temperature distribution** along the composite material including the **Nip Point**, as function of time.

Introduction
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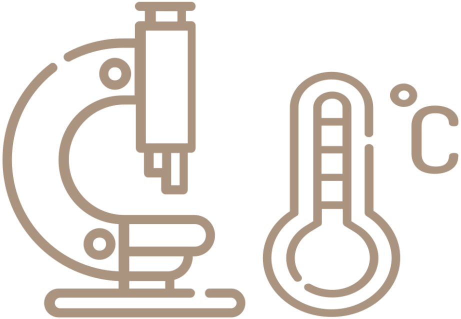
- Measurements:



Introduction
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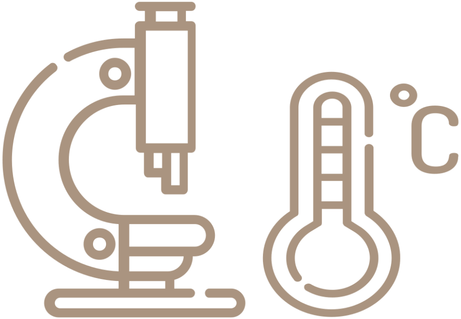

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- Estimate the **temperature distribution** along the composite material including the **Nip Point**, as function of time.

- Measurements:
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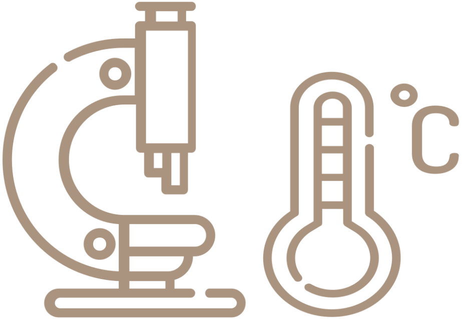
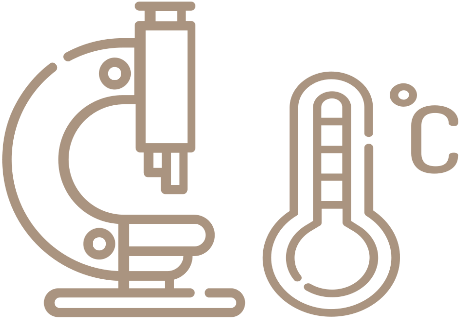
  - Thermal conductivity as function of temperature



Introduction
Objectives

- Estimate the **temperature distribution** along the composite material including the **Nip Point**, as function of time.
- Measurements:
  - Specific heat as function of temperature
  - Thermal conductivity as function of temperature
  - Thermal-optical properties as function of temperature



Materials and Methods

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Materials and Methods
Composite material

Toray Cetex - TC910
PA6 matrix base
Thermal properties according to its data-sheet:

- Glass transition temperature: 60 °C

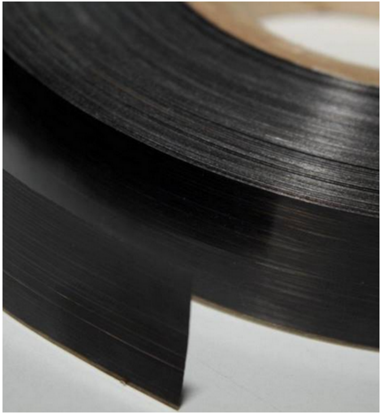


Figure 5. Composite material prepreg. PA6 matrix-based

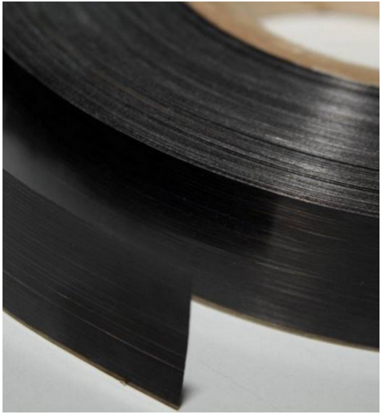
Materials and Methods
Composite material

Toray Cetex - TC910

PA6 matrix base

Thermal properties according to its data-sheet:

- Glass transition temperature: 60 °C
- Melting temperature: 233 °C



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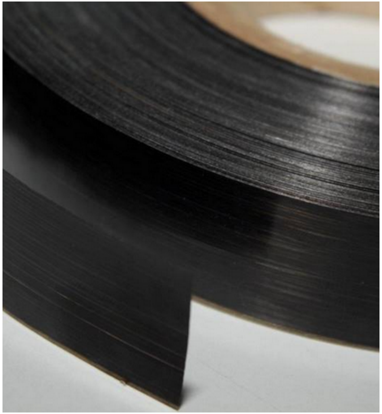
Materials and Methods
Composite material

Toray Cetex - TC910
PA6 matrix base
Thermal properties according to its data-sheet:

- Glass transition temperature: 60 °C
- Melting temperature: 233 °C
- Specific heat as function of temperature: **???**



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Toray Cetex - TC910

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- Glass transition temperature: 60 °C
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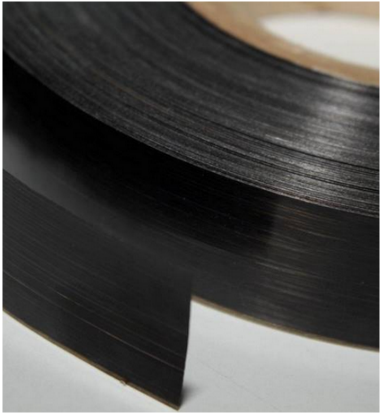
- Specific heat as function of temperature: **???**
- Thermal conductivity as function of temperature: **???**



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Materials and Methods
Composite material

Toray Cetex - TC910

PA6 matrix base

Thermal properties according to its data-sheet:

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- Specific heat as function of temperature: **???**
- Thermal conductivity as function of temperature: **???**
- Thermal-optical properties as function of temperature: **???**

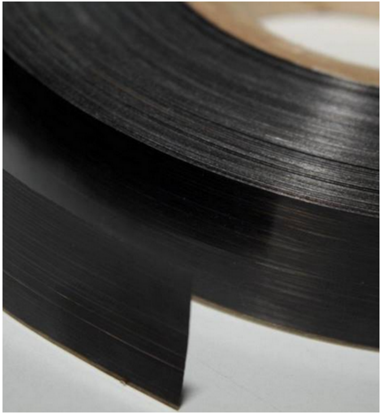


Figure 5. Composite material prepreg. PA6 matrix-based

Materials and Methods
Thermal characterization

Standard test procedures

SPECIFIC HEAT

- Standard test procedure:
  - ASTM E 1269-01
- Test apparatus:
  - Differential Scanning Calorimeter Q200 from TA Instruments.

Figure 6. DSC Q200 TA Instruments

Standard test procedures

THERMAL CONDUCTIVITY

- Standard test procedure:
  - Laser Flash method. ASTM E-1461

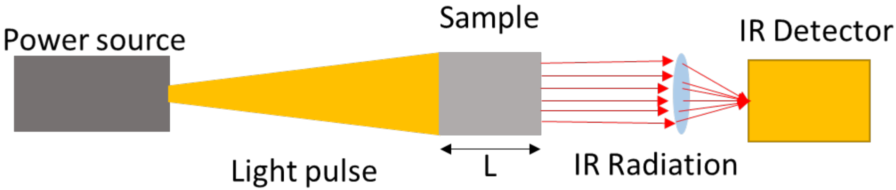


Figure 7. Laser Flash method working principle

Materials and Methods
Thermal characterization

Standard test procedures

THERMAL CONDUCTIVITY

- Standard test procedure:
  - Laser Flash method. ASTM E-1461

There **is no such machine** at INEGI's laboratory

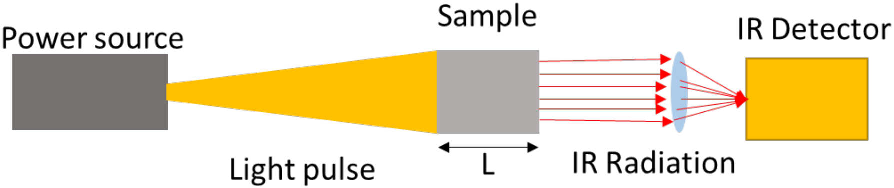


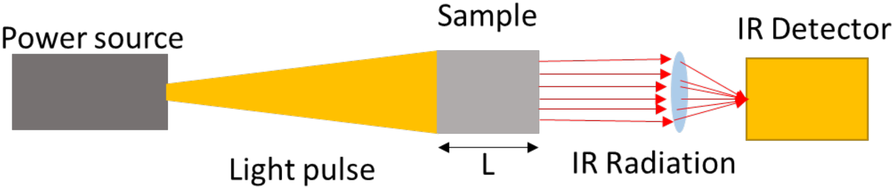
Figure 7. Laser Flash method working principle

Standard test procedures

THERMAL CONDUCTIVITY

- Standard test procedure:
  - Laser Flash method. ASTM E-1461

The machine only measures in **one direction**



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Materials and Methods
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THERMAL CONDUCTIVITY

- Thermal-Vacuum chamber
  - Pressures under 10^{-5} mPa

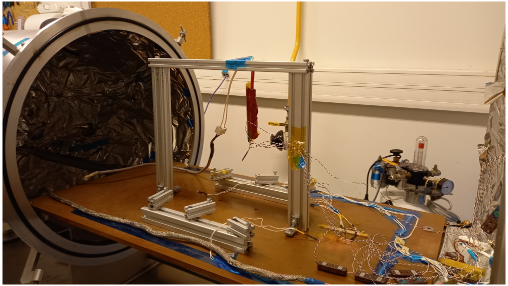


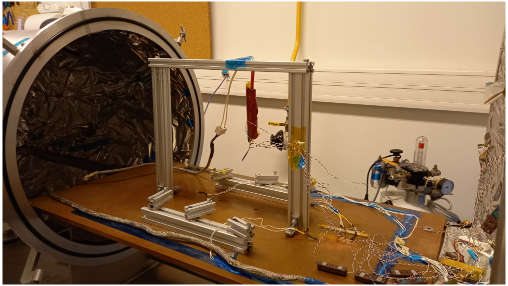
Figure 8. Thermal conductivity in-house procedure

Materials and Methods
Thermal characterization

In-house test procedures

THERMAL CONDUCTIVITY

- Thermal-Vacuum chamber
  - Pressures under 10^{-5} mPa
- No external interferences
  - Radiation
  - Convection



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In-house test procedures

THERMAL CONDUCTIVITY

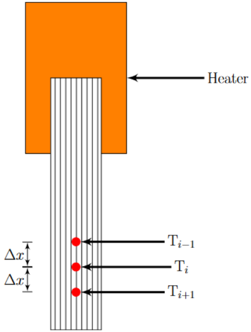

Figure 9. Thermal conductivity in-house procedure. Theoretical principle

$$\frac{dT}{dt} = \alpha_x \left(cp(T), \rho, k_x(T)\right) \cdot \left(\frac{d^2T}{dx^2}\right) \quad (3)$$

$$\frac{T_i^{p+1} - T_i^p}{\Delta t} = \frac{k_x(T_i^p)}{\rho \cdot cp(T_i^p)} \cdot \left(\frac{T_{i+1}^p - 2T_i^p + T_{i-1}^p}{\Delta x^2}\right) \quad (4)$$

Materials and Methods

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In-house test procedures

THERMAL CONDUCTIVITY

- The heater is an electrical resistance

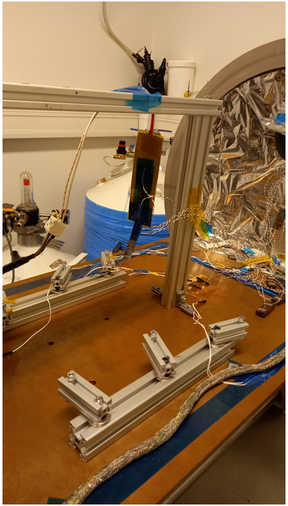

Figure 10. Thermal conductivity in-house test equipment

Materials and Methods
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THERMAL CONDUCTIVITY

- The heater is an electrical resistance
- The heater has an aluminium plate to conduct the heat from the resistance to the composite material

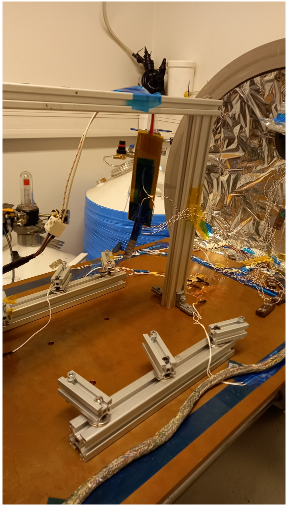

Figure 10. Thermal conductivity in-house test equipment

In-house test procedures

THERMAL-OPTICAL PROPERTIES

- Emissivity and absorptivity
- Reflectivity

Materials and Methods

Thermal characterization

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THERMAL-OPTICAL PROPERTIES

- Emissivity and absorptivity
- Reflectivity

Standard procedure to calibrate pyrometers

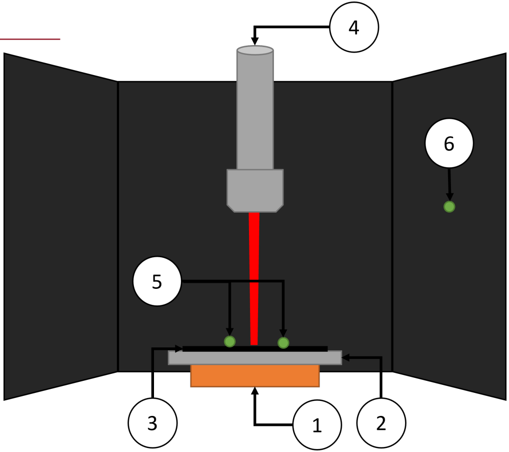


Figure 11. In-house designed test procedure for thermal-optical properties measurement

Materials and Methods
Thermal characterization

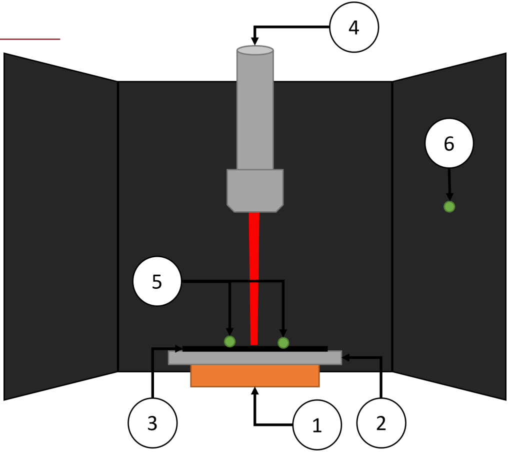
In-house test procedures

THERMAL-OPTICAL PROPERTIES

- Emissivity and absorptivity
- Reflectivity

Standard procedure to calibrate pyrometers

1. Heating element
2. Aluminium plate
3. Material sample
4. Pyrometer
5. Contact temperature sensor, material
6. Contact temperature sensor, ambient



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Materials and Methods
Thermal characterization

In-house test procedures

THERMAL-OPTICAL PROPERTIES

Basic correlations:

$$\varepsilon + \tau + \rho = 1 \quad (5)$$

$$\tau = 0 \quad \varepsilon \approx \alpha \quad (6)$$

$$\varepsilon + \rho = 1 \quad (7)$$

$$\varepsilon_{\mathrm{mat}} = \frac{\varepsilon_{\mathrm{pyro}} \cdot T_{pyro}^4 - T_{\mathrm{enclosure}}^4}{T_{\mathrm{mat}}^4 - T_{\mathrm{enclosure}}^4} \quad (8)$$

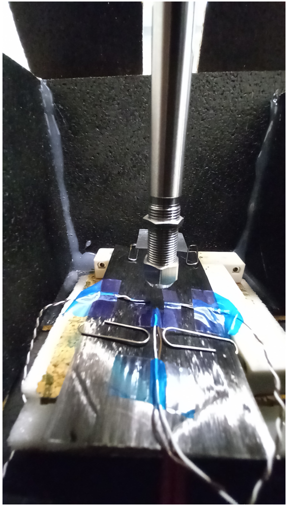

Figure 12. In-house designed test procedure

Results

3. Results
   3.1 Specific heat
   3.2 Thermal Conductivity
   3.3 Thermal-Optical properties
   3.4 Simulation

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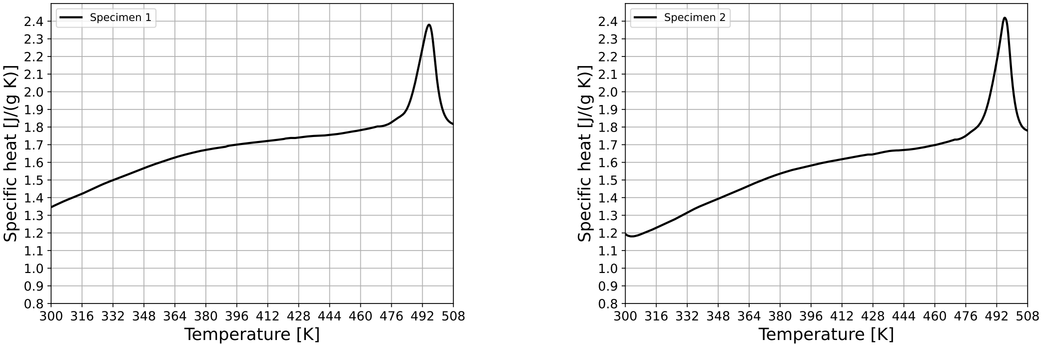
Specific heat

The results from the standard procedure for the composite material sample



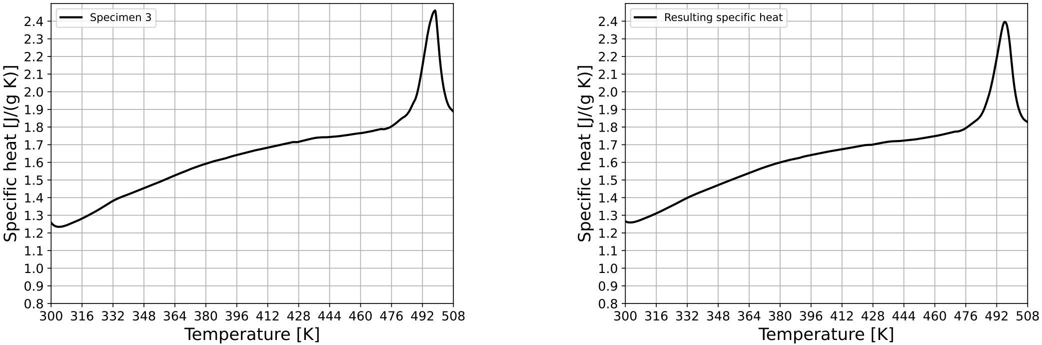
(a) Test sample 1 (b) Test sample 2

Figure 13. Specific heat results 1

Results
Specific heat

Specific heat

The results from the standard procedure for the composite material sample



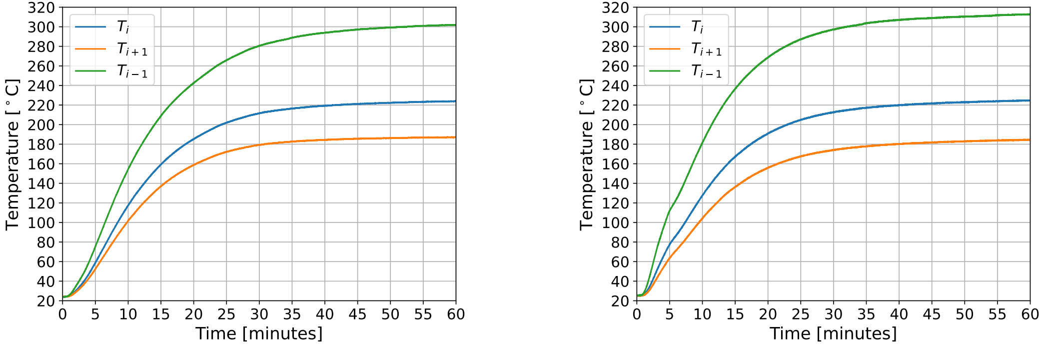
(a) Test sample 3 (b) Specific heat mean

Figure 14. Specific heat results 2

Results
Thermal Conductivity

Thermal conductivity

The results from the in-house designed procedure for the composite material sample

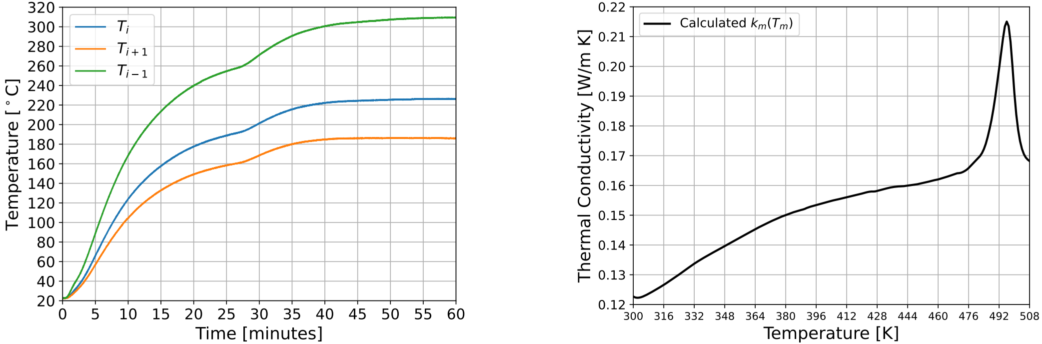


(a) Test sample 1 (b) Test sample 2

Figure 15. Thermal conductivity results 1

Thermal conductivity

The results from the in-house designed procedure for the composite material sample



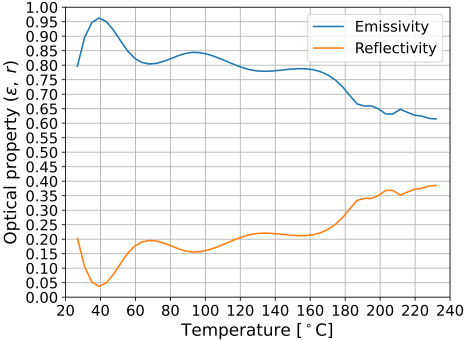
(a) Test sample 3 (b) Thermal conductivity mean

Figure 16. Thermal conductivity results 2

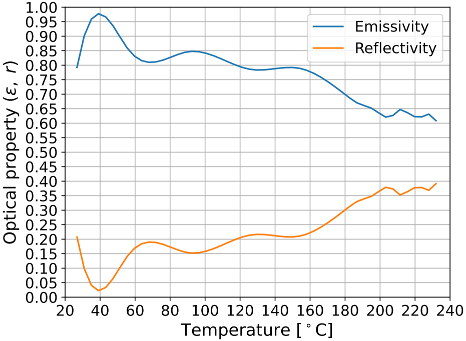
Results
Thermal-Optical properties

Thermal-optical properties

The results from the in-house designed procedure for the composite material sample



(a) Test sample 1

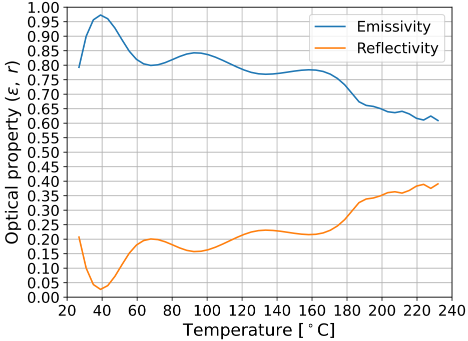


(b) Test sample 2

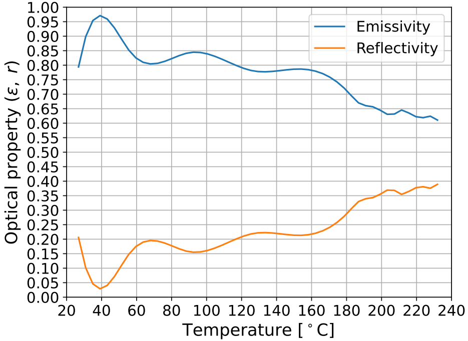
Figure 17. Thermal-optical properties results 1

Thermal-optical properties

The results from the in-house designed procedure for the composite material sample



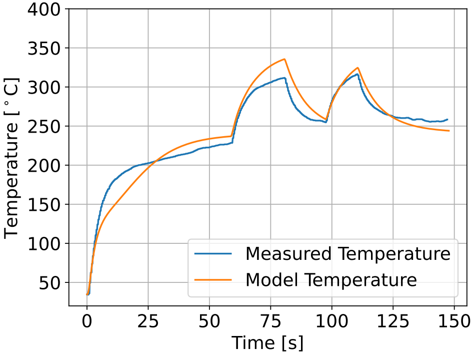
(a) Test sample 3



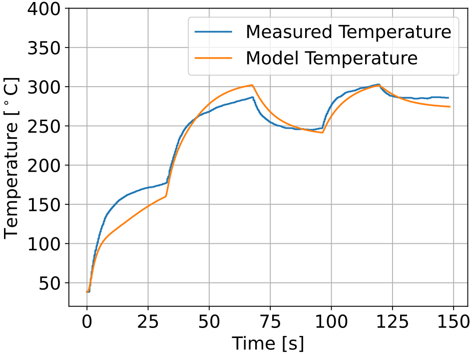
(b) Thermal-optical properties mean

Figure 18. Thermal-optical properties results 2

Test and simulation



(a) Test and simulation 1



(b) Test and simulation 2

Figure 19. Test and simulation on the real machine*

*J. de Sá Rodrigues, P. T. Gonçalves, L. Pina, and F. Gomes de Almeida, "Modelling the Heating Process in the Transient and Steady State of an In Situ Tape-Laying Machine Head," Journal of Manufacturing and Materials Processing, vol. 6, no. 1, p. 8, Jan. 2022, doi: 10.3390/jmmp6010008. [Online]. Available: http://dx.doi.org/10.3390/jmmp6010008

Conclusions

4. Conclusions

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Conclusions

- The Thermal conductivity test considers a uni-directional conductivity in a thin material sample, avoiding the convective effects.
  - Nonetheless, the radiation component has to be included into the fundamental equation to minimize the uncertainty.
  - Having a procedure which allows to neglect the convective effects, is significantly cheaper than producing material samples to measure the thermal conductivity perpendicular to the fibres.
- The thermal-optical test procedure, as a procedure to calibrate the optical readings of a pyrometer, allows to obtain the emissivity values as function of the composite material temperature.
  - This characteristic, allows to use any pyrometer available, including pyrometers with factory fixed parameters.

Conclusions

- The proposed methodology for thermal characterization of a composite material, specifically unidirectional prepregs, contributed to predict the temperature of the measuring point for the ATL process.
  - Knowing the composite properties, allows to fine adjust heat transfer parameters, minimizing the uncertainties.
  - The temperature distribution can be estimated then, a model-based control strategy can be applied, for example, a Model Predictive Control strategy.

Acknowledgements

5. Acknowledgements

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