MONITORING RTM PROCESS BY OPTICAL FIBER SENSOR

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1 Introduction

The Resin Transfer Molding (RTM) process is widely used for manufacturing Composite parts with complex shapes and high mechanical performances. The difficulty to settle the process parameters and the complexity of the resin flow can lead to scrap parts. In fact, the parameters of the process are often adjusted by trials and operator experience. The result is an increase of the development cost for composite manufacturing part. Therefore the development of a part with a complex geometry or different material architecture clearly requires the improvement of process reliability.

This goal can be reached with a better knowledge of the physical phenomena which take place during the process. Optical fiber based sensors are efficient tools to optimize the composite material processing in real time. Some authors have already used optical fiber sensors for autoclave process [1,2] and recently for RTM monitoring [3].

The objective of the paper is to introduce a new type of Fiber Bragg Grating (FBG) *in-situ* sensor to monitor composite plate RTM processing. The final aim of the research is to analyze the influence of the process parameters upon the quality of the part by using this new sensor.

2 Optical fiber sensor (OFS)

2.1 Fiber Bragg Grating (FBG)

OFS such as Fiber Bragg Grating (FBG) are suitable for monitoring composite material process due to their low invasivity. The advantage of FBG on other sensors is that they give access to physical parameter inside the material. Therefore, they can be applied to the study of thick laminates and give assess to the occurrence of residual strain or exothermic phenomena. Usually, a FBG consists of a periodic variation of the core refractive index along the optical fiber. The response of FBG to an incident broadband light source is one special wavelength which is called the Bragg's wavelength λ_B.

The variation of λ_B depends on the longitudinal strain and the temperature through a linear relationship:

$$\frac{\Delta\lambda_B}{\lambda_B} = K_T.\Delta T + K_\varepsilon.\Delta\varepsilon \qquad (1)$$

The difficulty to use FBG in composite application is to discriminate the strain and the temperature, both of which depending on time. Some authors use thermocouples to measure the temperature locally. Nevertheless, this method increases the invasivity of the sensor. Another method is applied here which originally was proposed by Shu et al. [4] by using two different types of FBGs: FBG type IA and type IIA inscribed in the same optical fiber. According to the authors, their different sensitivities result in the determination of the temperature and the strain with an accuracy of 1°C and 20 με respectively.

The advantage to use dual grating is that measurements can be performed in real time. Afterwards, these measures can be used to validate model to predict of residual strain.

2.2 Dual Bragg grating method

This method uses two FBGs with different sensitivities to the strain and the temperature. In this way we can extend the relation (1) to this form:

$$\begin{bmatrix} \frac{\Delta\lambda_1}{\lambda_1} \\ \frac{\Delta\lambda_2}{\lambda_2} \end{bmatrix} = \begin{bmatrix} K_{\varepsilon_1} & K_{T_1} \\ K_{\varepsilon_2} & K_{T_2} \end{bmatrix} \begin{bmatrix} \Delta\varepsilon \\ \Delta T \end{bmatrix} \qquad (2)$$

Where the suffixes 1 and 2 refer to the different Bragg's sensor. We assume that the response of the FBG to the temperature and the strain is linearly, and the cross sensitivity negligible.

Thus temperature and strain can be determined by measuring the shifts of the two Bragg wavelengths. This method is limited by the condition of the matrix sensitivity. In fact, each FBG must have different sensitivities in order to allow the inversion of matrix. In this study, special FBGs have been designed and elaborated by the Hubert Curien Laboratory (FRANCE). The FBGs type IIA and IA are inscribed respectively in hydrogenated optical fiber and hydrogen free optical fiber, with a long period of UV exposure. Figure 1 describes the spectral reflection of the three kind of FBG.

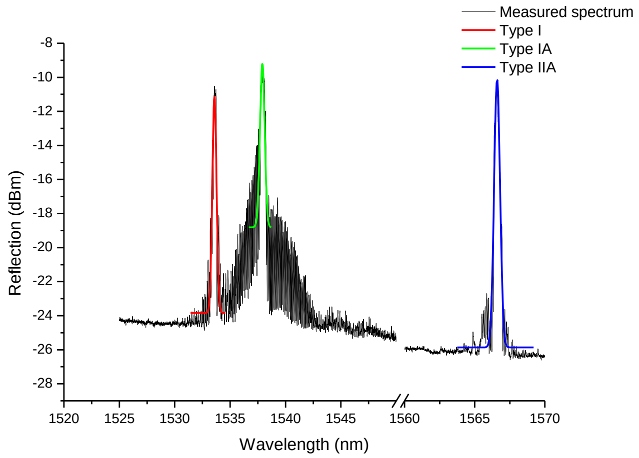

Fig. 1 The spectral response of different FBG types

Each FBG is subject to a thermal cycle in order to assure a thermal stability of the sensor. Afterward the FBGs are calibrated to measure the strain sensitivity Kε and thermal sensitivity K_T. Table 1 resume the sensitivities obtained from the FBGs which were manufactured in this study.

	Kdéf pm/ε	KT pm/°C
TypeI	1,24	9,28
TypeIA	1,24	9,37
TypeIIA	1,27	9,87

Table 1 Thermal and strain sensitivity

As it was expected, the strain sensitivity is almost the same for all type of FBG. However we can observe some difference for the thermal sensitivity.
Different schemes of discrimination was tested and evaluated theoretically through the study of propagation errors made by the measure of Bragg's wavelength. The maximum errors in strain and temperature are listed in Table 2.

	Température errors °C	Strain errors με
Scheme Type I/IA	20	170
Scheme Type I/IIA	7	50

Table 2 Maximum temperature and strain errors for different schemes

The scheme with Type I and type IIA can lead to small error in strain but poor temperature resolution. This error is not acceptable for the monitoring of process. Therefore we must still improve the difference in thermal sensitivity of these FBGs by working on the FBG IA/IIA elaboration.
For this reason we have utilized thermocouple to discriminate temperature and strain in the next part of this article.

3 Case study of RTM process monitoring

3.1 Material and experimental set up

Optical fiber with FBGs are embedded in the central part of the preform. A thermocouple is located near the FBGs to validate the temperature measurement.
The preform here is composed of 7 Unidirectional carbon layers with the following sequence $[90_2, 0_3, 90_2]$. The size of the final plate is 430 x 430 x 4 mm^3.
The resin RTM6® is preheated to 80°C and injected with a constant rate inside the mould. The filling stage takes about 10 min. Then, the cure cycle recommended by the supplier is applied to the mould to consolidate the material.
The main process steps are:

- preforming and debulking of preform under vacuum (1);
- injection of resin through the preform inside the mould at 120°C (2);
- curing at 180°C during 90 min (3);
- cooling to the room temperature (4).

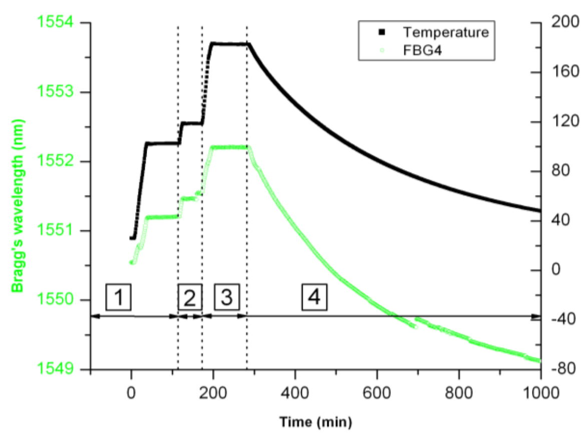

Fig 2. Temperature and strain measurement during RTM process.

Figure 2 shows the evolution of the Bragg's wavelength of the FBG embedded in composite material all along the process.

3.2 Results

At first, we try to evaluate the mechanical state of the material, with uniaxiale assumption.

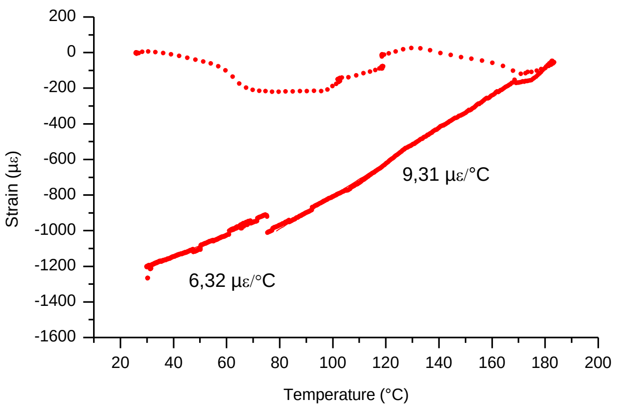

Fig. 3 Strain evolution during the RTM process

Figure 3 reveals that there is a discontinuity of the strain response during the cooling stage (4), which is related to the part/mould interaction. The difference between the CTE of the composite material (α_c=5.10^{-6}/°C) and the aluminum mould (α_M=23.6.10^{-6}/°C) leads to the debonding of the part and mould when the maximum shear strength is reached. This influence is one source of residual stress which needs to be minimized to guarantee the dimension stability of the final part.

We can achieve a better evaluation of the mechanical material state with an inverse analysis that takes account of the optical fiber perturbation inside the material and the transverse stresses.

4 Inverse analysis

During the cooling stage we have noticed a slight splitting of the peak issued from the FBG sensor, as shown in figure 4. In fact, this phenomenon is due to the thermal contraction of the material which results in optical fiber sensor transverse stresses. This phenomenon is called the birefringence.

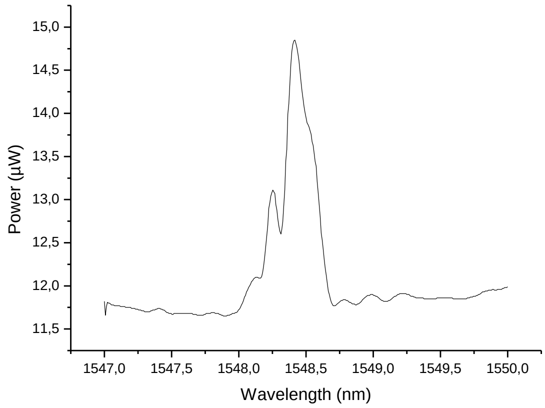

Fig. 4 Spectral response of the FBG in the end of cooling stage

This spectral response of our sensor means that we must assessed the mechanical state of the material in order to link the Bragg's wavelength shifts to the strains inside the material.

The approach suggested here was used earlier by Van Steenkiste and Kollar [5] and more recently by Vacher [6]. It consists to determine the relation between the farfield strains in the material and the strains inside the sensor. These strains correspond to the strains which would exist without the disturbance of the sensor. Moreover the perturbation caused by the inclusion of optical fiber is determined by the theory of elasticity of an anisotropic body [7]. Accordingly we can deduce analytically a strain matrix transfer.

After that we can utilized a photoelastic model to calculate the Bragg's wavelength shifts caused by the strains inside the sensor. Figure 5 resume the steps of the model. By inverting this schema, it may be possible to deduce the mechanical strains inside the material from the Bragg's wavelength shifts. Therefore these farfield strains represent the mechanical state of the material.

We have applied this model to the measures resulting from the monitoring of RTM process during the cooling stage. The results are compared to results issued from Classical Laminate Plate Theory (CLPT).

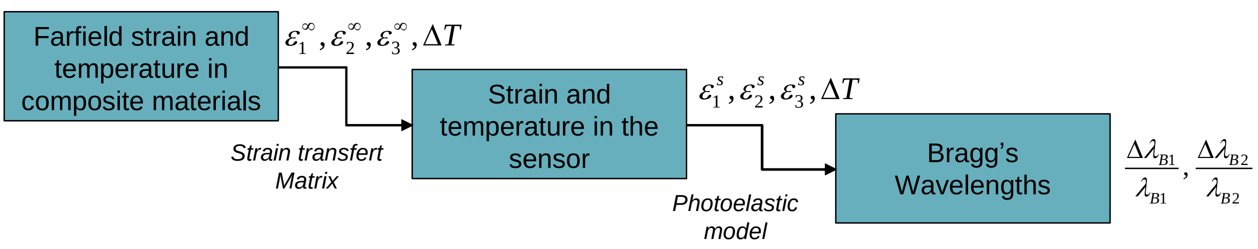

Fig. 5 Relations between the parameters

The geometry of composite laminate with optical fiber (OF) is given in figure 5.

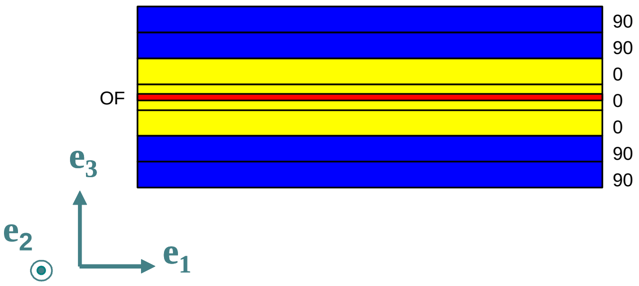

Fig. 5 Representation of the laminate

Table 3 resume the bragg's wavelength shifts which were measure during the cooling stage.

Δλ1	Δλ2
-2.848 nm	-3.008nm

Tab. 3 Bragg's wavelength shifts during the cooling stage

The farfield strains are shown in the table 4.
As it was expected, we observe that the laminate is in compression state due to the thermal contraction effects. The CLPT confirmed the level of these values.

Directions	Experimental measures	CLPT
e_1	-973 με	-622 με
e_2	-190 με	-432 με
e_3	-8819με	-8862 με

Tab 4 Comparison between experimental measures and CLPT theory

It is noticeable that the strain along the sensor is close to the numerical prediction. The value obtained with uniaxiale assumption is more distant because the transverse strains are reduced to the optical fiber poisson effects. Therefore uniaxiale assumption can lead to large errors, but give easily a quantitative value of the strain inside the laminate during the process. In the case of fine analysis we have to set-up model to assess the mechanical strains at the end of the process.

Conclusion and perspectives

As expected, optical fiber sensors can be relevant tools to monitor physical parameter as the temperature and the strain development inside the part during the RTM process. These parameters should be kept under control during the processing, and to guarantee the reliability of the process.
The highlight of this dual grating method is that several sensors can be multiplexed in the same optical fiber. Thus measurements of the temperature and the strain can be achieved at different locations of the part without introducing thermocouples, so the invasivity of *in-situ* sensors is fairly reduced.
Nethertheless the measure of the strains inside the material must be treated in parallel with a model to take account of the transverse effects which dominate the cooling stage of the process.
This instrumentation will be extended to the study of the elaboration of thick parts and flat panels with thickness variation to assess the effects of parameters process to the final part.

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