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Abstract: Markets with a strong aesthetic component need constant innovation in concept generation and materials. The development of these materials is extremely dependent on a technological support that could be complemented with monitoring systems. This study presents the development of in-situ monitoring system used in the manufacturing of a natural fiber composite basin using RTM technology. The sensing technology selected for this work was the optical fiber Bragg Grating (FBG) sensors due to advantage such as, electromagnetic interference immunity, small size, good corrosion resistance, ultimate long-term reliability, direct absolute measurement, low cost, embedding possibility and unique wavelength-multiplexing capability.
FBG sensors and a thermocouple selected for this application are meant to take measurements of longitudinal strain and temperature. Two physical parameters that occur in the resin flow and cure crucial for understanding this process.
The aim of this study is to detect the resin flow front in-situ and in real-time in the RTM process. The FBG sensors are sensible to temperature variation through thermal expansion, making it very difficult to disassociate this phenomenon from the strain caused by the resin flow front.

The use of these sensors allowed to detect the complete filling of the mould and determine the exothermic peak.

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I, Ms. Celia Novo, the first author of present paper, tilted "Monitor of a RTM Prototype Using Fiber Bragg Grating Sensors", confirms that all authors were fully involved in the study and preparation of the manuscript and that the material within has not been and will not be submitted for publication elsewhere.

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MONITORING OF A RTM PROTOTYPE USING FIBER BRAGG GRATING SENSORS

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1. INTRODUCTION

The present work describes the phases of a prototype development to obtain a sanitary wash basin in coconut random mat with epoxy resin. The geometry was highly complex with 12mm uniform thickness walls with cylindrical and symmetric curvatures, an external geometry without bubbles and local resin concentration. For these reasons RTM light was chosen as the most suitable production technique. However the random fiber was too porous and the composite production techniques concepts must be adapted for this fiber hence great care should be taken for proper injection strategy. The mould and males were studied and designed considering all factors. FBG sensors and a thermocouple were placed to monitor the strain and temperature in loco and real time to understand the behavior of resin flow front [1-4]. The results obtained in the product development will facilitate the optimization technology production for faster implementation in industrial lines.

2. EXPERIMENTAL

2.1. MATERIALS SELECTION AND MOULD CONCEPTION

The dimensions of the wash basin were 430mm diameter, 120mm high and 12mm thick. The materials used for the prototype were random mat coconut fiber with

1482g/m^2 (98.9 kg/m^3 density) and 15mm thick. The selected matrix was epoxy for its good resistance to chemicals, low shrinkage and transparency, which confer a natural color of coconut, and also medium viscosity 600mPa.s that allow a good injection [5, 6].

The moulds and males were studied and designed considering all factors considered above, and furthermore concerning the fiber porosity, resin viscosity, demoulding the entire prototype, strategy of injection (inlet and outlet of resin and vacuum points) and thin wall. The injection strategy was two points of inlet resin, with a runner on the lower side of the mould to oblige the resin to fill the cavity from the bottom to the top, and the outlet resin with vacuum in a central point and also in a upper ring channel with two outlet points.

The wash basin model was obtained by machining a high density polyurethane block and finished with a fine gloss paint coating. Hence the mould was produced in glass fiber and polyester resin divided in three parts, to allow demoulding from half sides. Two males were assembly inside the mould, one rigid in polyurethane resin charged with aluminum powder, and the second flexible in silicone rubber, to allow demoulding easily the inside part with negative draft (Fig. 1).

1. SENSOR BRAGG THEORETICAL CALCULATIONS

A FBG is a periodic modulation of the refractive index of the core of a single mode optical fibre, written by exposure to UV light in the region around 248 nm [7]. This fabrication process is based on the photosensitive mechanism, which is observed in Ge-doped optical fibres [8]. If broadband light is travelling through an optical fibre containing such a periodic structure, its diffractive properties promote that only a very narrow wavelength band is reflected back. The centre wavelength of this band can be represented by the well known the Bragg condition:

$$\lambda_B = 2n_{eff}\Lambda \qquad (1)$$

Where λ_B is the centre wavelength, n_{eff} is the effective index of the guided mode and Λ is the period of the index modulation. The FBG resonance wavelength will vary accordingly with temperature or strain changes experienced by the fibre. For a temperature change ΔT, the corresponding wavelength shift is given by:

$$\Delta\lambda_B = \lambda_B\left(\frac{1}{\Lambda}\frac{\partial\Lambda}{\partial T} + \frac{1}{n}\frac{\partial n}{\partial T}\right)\Delta T = \lambda_B(\alpha + \xi)\Delta T \qquad (2)$$

Where α is the fibre thermal-expansion coefficient, and ξ is the fibre thermo-optic coefficient. The wavelength shift, induced by a longitudinal strain variation $\Delta\lambda_B$ is given by,

$$\Delta\lambda_B = \lambda_B\left(\frac{1}{\Lambda}\frac{\partial\Lambda}{\partial\varepsilon} + \frac{1}{n}\frac{\partial n}{\partial\varepsilon}\right)\Delta\varepsilon = \lambda_B(1 - p_e)\Delta\varepsilon \qquad (3)$$

Where p_e is the photoelastic coefficient of the fibre, for a silica fibre, the wavelength-strain and wavelength-temperature sensitivities are ~13 pm/ºC and ~1.15 pm/µε, for a Bragg wavelength centred at 1555 nm for standard single mode fibres [9].

2.2. MONITORING SYSTEM AND RTM PROCESSING

The facility of multiplexing fiber optic sensors allow one fiber with five gratings, however the complex geometry of the mould might predict problems in positioning the sensor in right places. Hence FBG sensors system planned for monitoring were two groups of two multiplexing optic fibers one with three sensors and the other with one sensor localized strategically in preferential places of resin flow front and in opposite mould side (Fig. 2).

The optical fibers were connected to a Braggmeter that records data in real time. A thermocouple was placed near FBG 2 and connected to a PC with acquisition card. The sensors were placed inside the mould wall, and the optical fibers and thermocouple wire were brought to the external, through a hole drilled in the vacuum seal ring and sealed with an epoxy resin, and then connected to its respective apparatus.

After the application of a liquid release, the preform of coconut mat fiber was placed inside the mould, following the silicon rubber and the rigid males, and then the mould was closed with a vacuum pressure of $0.2x10^5$ Pa through the vacuum seal ring (see Fig. 3).

Due to the complexity of assembling mould, coconut preform and males, when the close operation was performed, some FBG sensors were submitted to high strains, resulting in an undesirable broken of them, remaining only three active FBG gratings and one thermocouple (Fig.4).

The epoxy resin was mixed with the hardener and placed in a pressure vessel, hence the injection started with $1x10^5$ Pa and the cavity mould under $0.6x10^5$ Pa of vacuum. The time of injection was 36min but only at 40min the resin inlet and outlet pipes were closed, so air bubbles in the resin front were allowed to leave out the mould. The resin start to cure and polymerization occur and after 24 hours the piece was demoulded (see Fig. 5).

3. MONITORING RESULTS

Since the mould is closed it turns a blind process, questions and doubts arise to end the injection at the right moment with the cavity saturated with resin and without bubbles. The FBG sensors and thermocouple were expected to measure variations when the resin flow front cross them and help to optimize the injection technology. Although as soon as the mould was closed with vacuum ($0.2x10^5$ Pa) and also applied lower vacuum in the cavity ($0.6x10^5$ Pa) the strain sensors detected variations. The vacuum seal ring is directly connected to the vacuum pump, without a pressure control valve, when the vacuum is reduced till $0.4x10^5$ Pa the vacuum pump started again to stabilize to the desired vacuum level, originating a higher compression of the perform and consequently an increasing of the strain in FBG. This phenomenon can be observed in the graphic results (Fig. 6-8) being the curve with a sinusoidal shape that cause some problems to understand the graphic.

The injection started at 200s after the reset of sensors system, the sequence of resin arrival was firstly at FBG2 (930s) after 150s to thermocouple, followed FBG1 (1730s) and finally FBG3 (1790s). The resin firstly arrived at the lateral outlets (1810s) followed by the central outlet (2160s). The injection end was at 2400s all pipes were closed just remaining the vacuum seal ring (see Fig.6).

FBG2 sensor and thermocouple were located nearby however the response was first detected in FBG2 and only 150s after reach the thermocouple (see Fig. 7). This is explained by the circular flow front of the resin fill, the measure of FBG sensor is in the vertical length, of 20mm, and the thermocouple was in just one local point, at FBG half length (medium velocity of flow front is 3mm/min).

The resin reached FBG 1 at 1730s and FBG3 at 1790s (see Fig. 8).

4. DISCUSSION OF RESULTS

RTM light uses a vacuum ring to seal the mould however when FBG sensors are used to monitor the injection the effect of variations due to vacuum pump are undesirable as results can lead to misunderstanding. This problem can be avoided using a rigid close up mould or applying a control valve to maintain vacuum steady.

The Analysis of graphic results demonstrates that the resin arrival was detected by temperature effects instead of strain variations. The differential of temperature between resin and mould was 1.5ºC, measured by the thermocouple.

In the end of injection the FBG sensors were submitted to irregular strain variations due to resin front containing air bubbles originating a turbulent flow which changes in flow pressure. This behavior allowed observing resin flow front arrival at FBG1 and FBG3.

The possibility of the detection of resin arrival using fiber Bragg Grating sensor has been understood and validated. These network of optical sensors are helpful to optimize RTM injection being a guide inside the mould giving data in loco and real time about resin flow front.

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Figure 1 – Schematic of mould, males and prototype.

Figure 2 – Schematic of FBG Sensors Positioning

Figure 3 – (from top to bottom) middle and bottom mould, middle and bottom mould with perform, complete mould before injection.

Figure 4 – Positioning of the remaining 3 sensors (top), Positioning of thermocouple with sensors.

Figure 5 – Coconut fiber wash basin.

Figure 6 – FBG sensors wavelength variation during the monitoring process.

Figure 7 – FBG2 and thermocouple measurements.

Figure 8 – Resin arrival in sensors FBG 1 and 3.

Figure 1

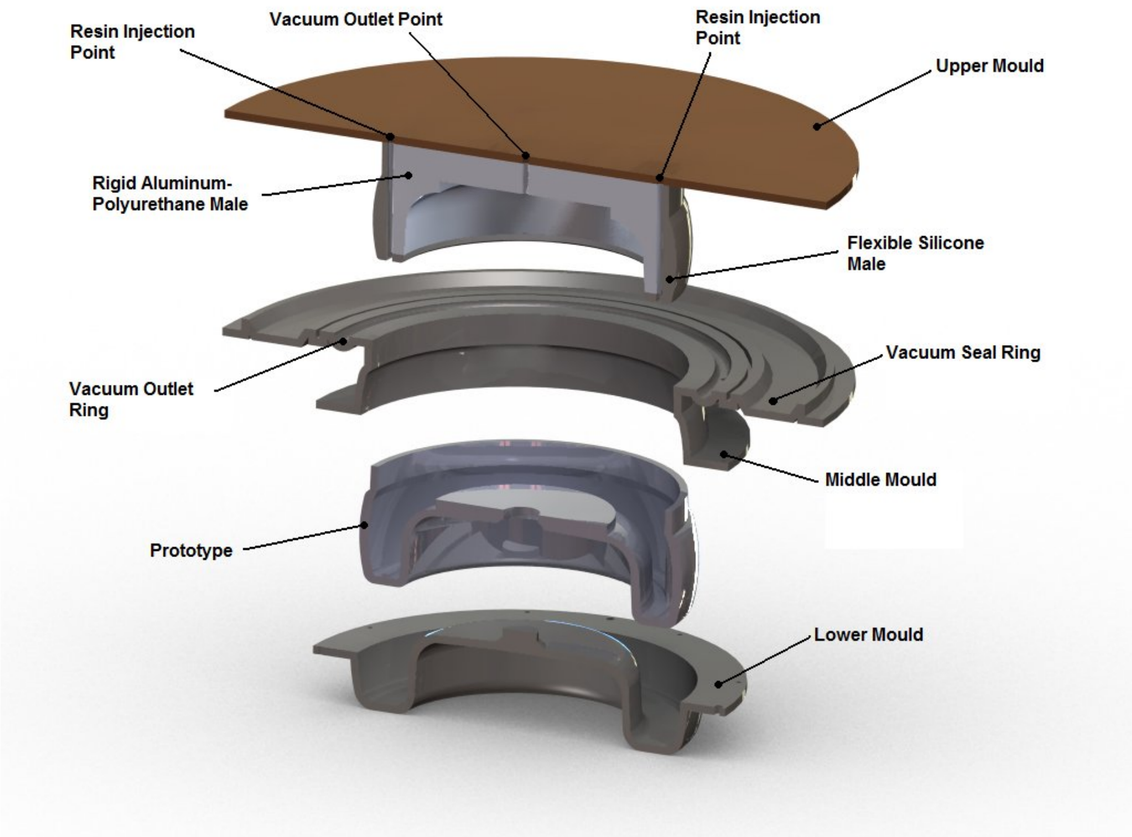
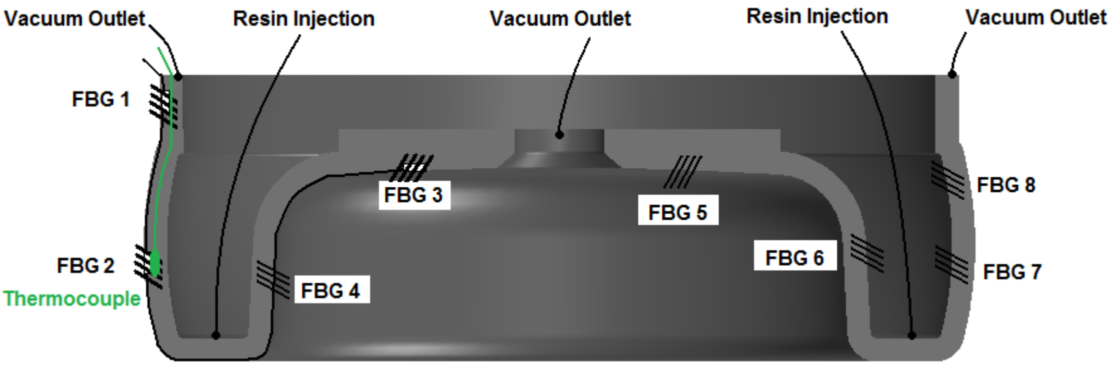

Resin Injection
Point
Vacuum Outlet Point
Resin Injection
Point
Upper Mould
Rigid Aluminum-
Polyurethane Male
Flexible Silicone
Male
Vacuum Seal Ring
Vacuum Outlet
Ring
Middle Mould
Prototype
Lower Mould

Figure 2



Vacuum Outlet
Resin Injection
Vacuum Outlet
Resin Injection
Vacuum Outlet
FBG 1
FBG 3
FBG 5
FBG 8
FBG 6
FBG 2
Thermocouple
FBG 4
FBG 7

Figure 3

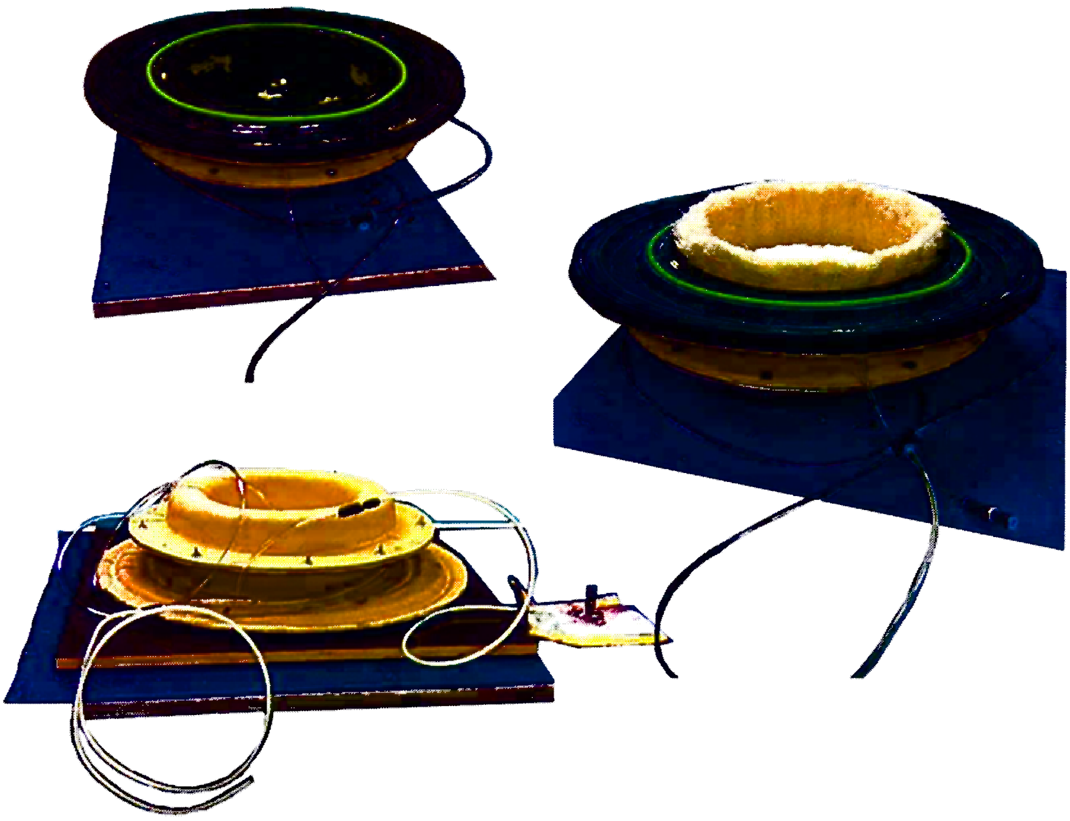


Figure 4

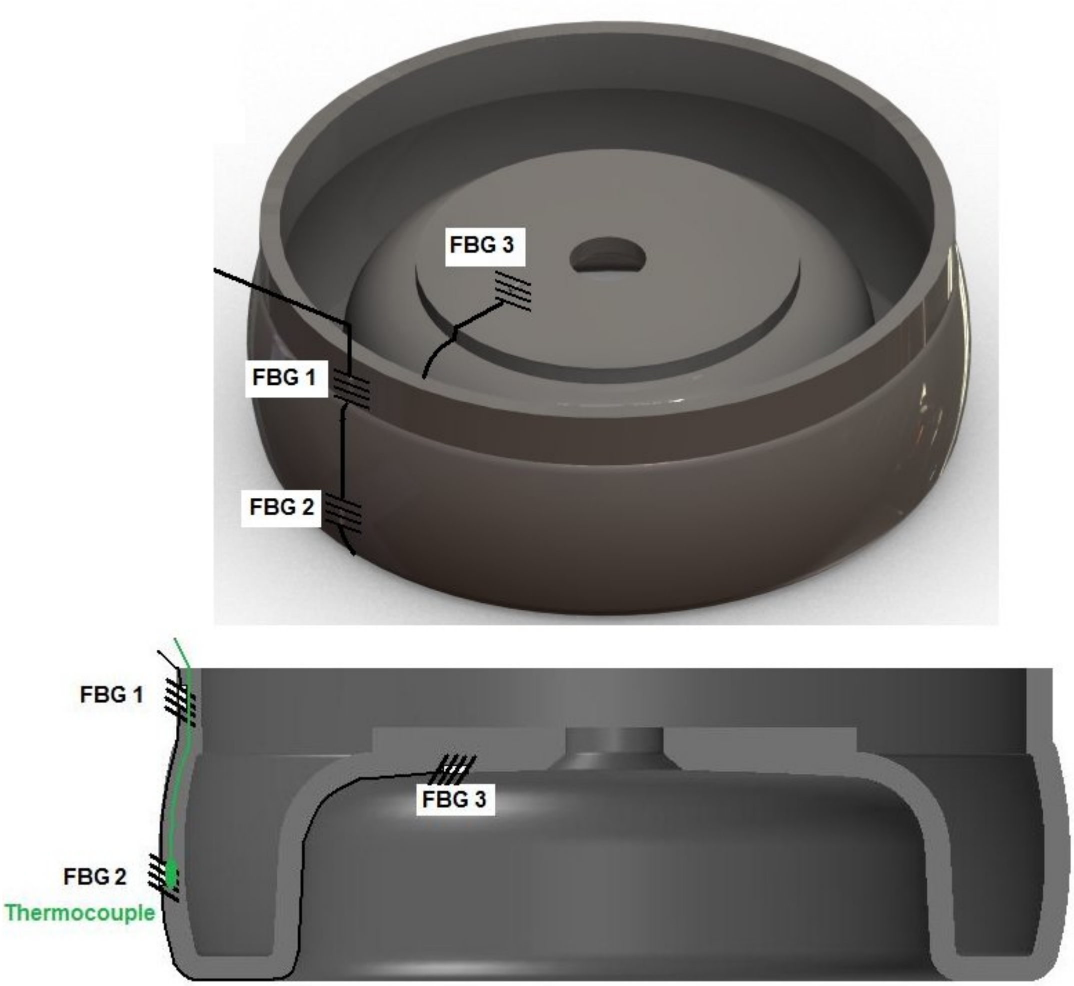
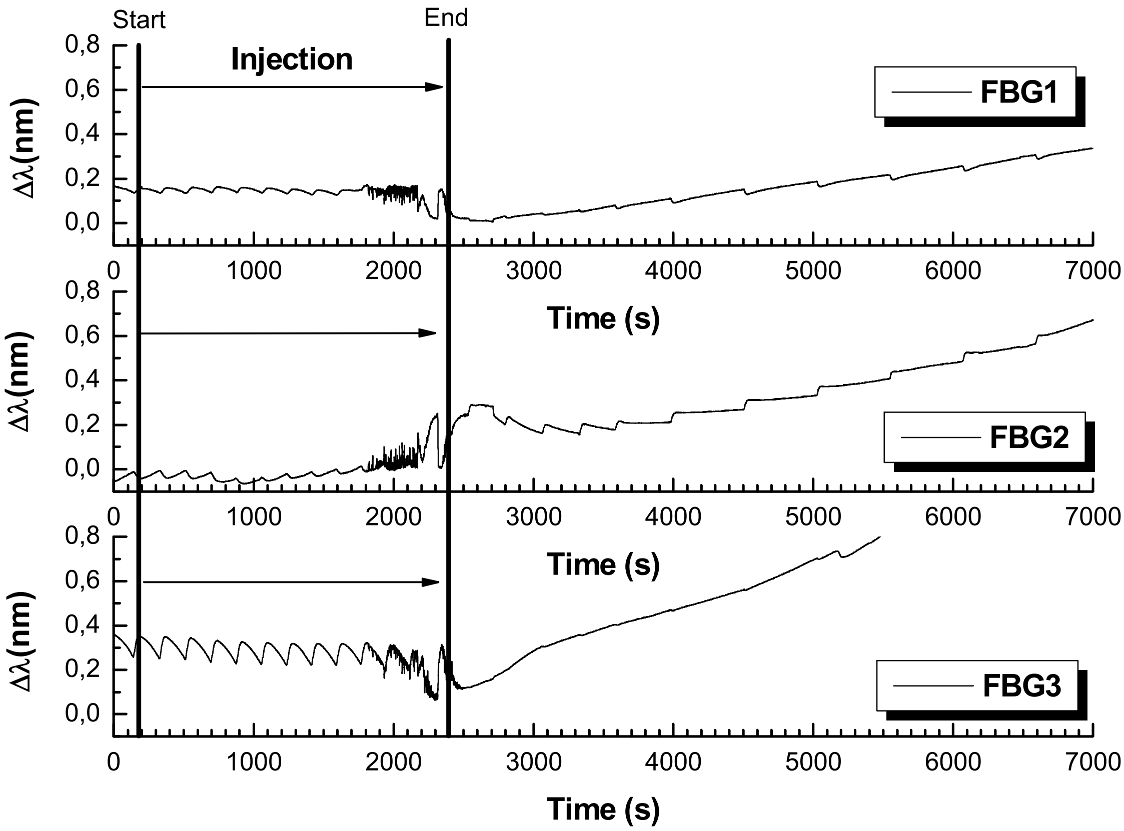


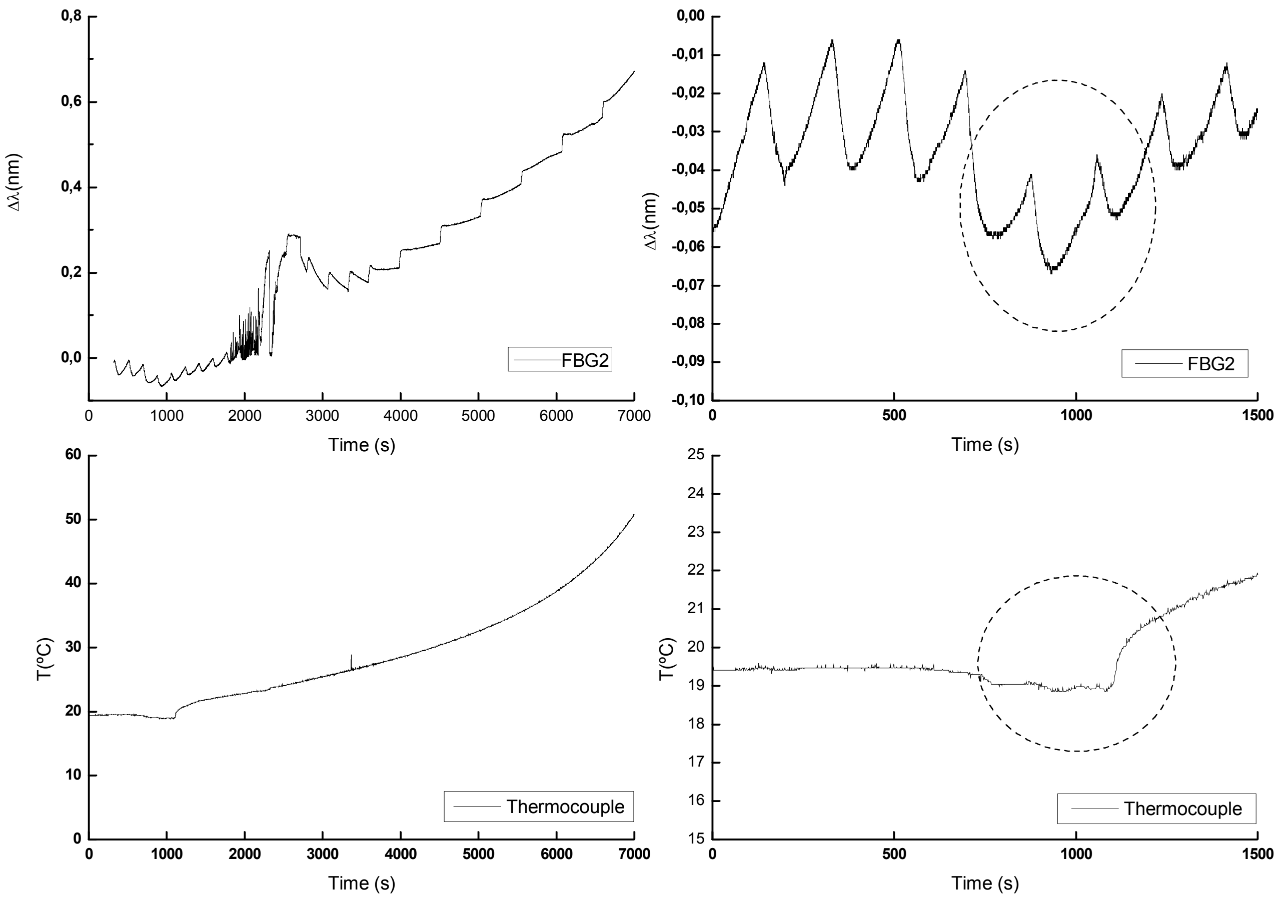
Figure 5

Figure 6



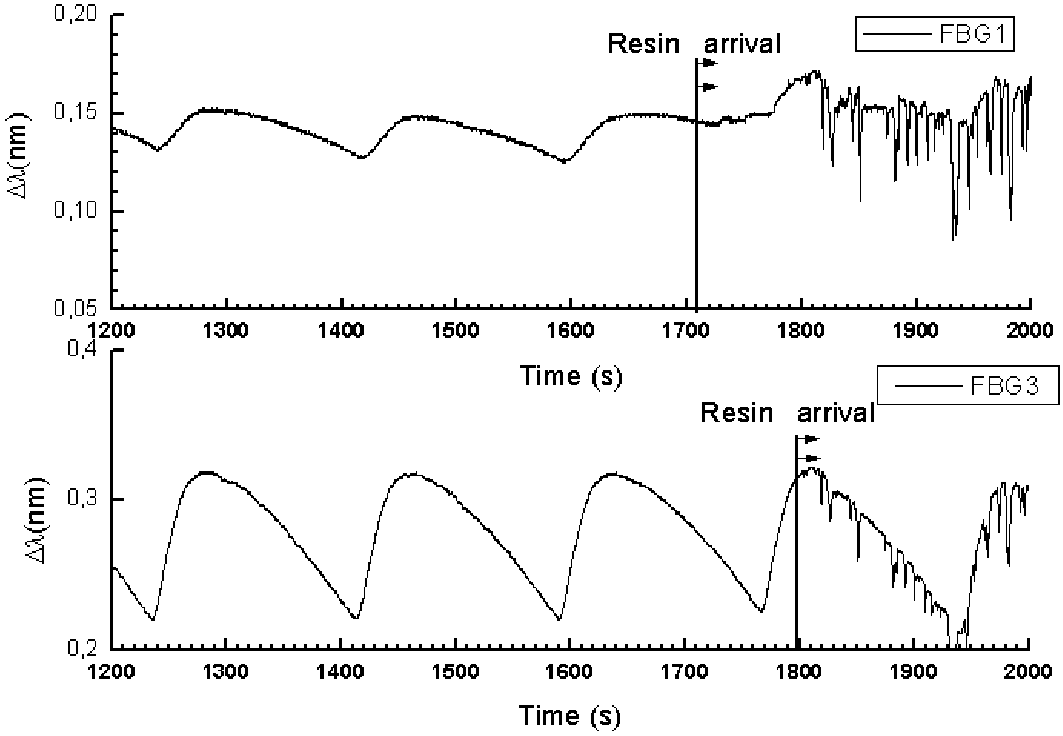
Start
End
Injection
FBG1
FBG2
FBG3
Δλ(nm)
Time (s)
0,8
0,6
0,4
0,2
0,0
0
1000
2000
3000
4000
5000
6000
7000

Figure 7



0,8
0,6
0,4
0,2
0,0
Δλ(nm)
FBG2
0
1000
2000
3000
4000
5000
6000
7000
Time (s)
0,00
-0,01
-0,02
-0,03
-0,04
-0,05
-0,06
-0,07
-0,08
-0,09
-0,10
Δλ(nm)
FBG2
0
500
1000
1500
Time (s)
60
50
40
30
20
10
0
T(ºC)
Thermocouple
0
1000
2000
3000
4000
5000
6000
7000
Time (s)
25
24
23
22
21
20
19
18
17
16
15
T(ºC)
Thermocouple
0
500
1000
1500
Time (s)

Figure 8


FBG1
Resin arrival
0,20
0,15
0,10
0,05
Δλ(nm)
1200
1300
1400
1500
1600
1700
1800
1900
2000
Time (s)
FBG3
Resin arrival
0,4
0,3
0,2
Δλ(nm)
1200
1300
1400
1500
1600
1700
1800
1900
2000
Time (s)