Cycle Time Optimisation of RTM Process with Optical Fibre Bragg Sensors

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ABSTRACT

The monitoring and control of RTM process in composite materials is important to reduce cost production and to obtain components with better quality at the first time. In this research programme, fibre Bragg sensors are used to optimise the process cycle time and also to find out defects during the component processing.

Optical fibre Bragg sensors offers great potentialities as they can be embebbed between layers of composite materials and, in just one optical fibre, it is possible to have several sensors. These sensors allow the determination of temperature profiles during injection and time polymerisation. Hence, it is possible to determine the right time to heat and cool the mould to speed up cycle production. Therefore, if the sensors are strategically positioned inside the mould, when the resin reaches each sensor it gives a signal that confirms that the area around the sensor has been well impregnated.

In this paper, several experiments are described in which an on-line system based on fibre Bragg sensors was implemented to monitor and control the RTM process.

1. INTRODUCTION

Resin transfer moulding (RTM) is a production process for polymeric matrix composite materials[1,2]. The process consists in laying down dry fibre of generally glass fibres by layers or multiaxial tissues, eventually also as a perform, in a closed mould. After closing the mould the resin is injected at low pressure and assisted with vacuum. In RTM, moulds can be built of metal or composite materials. Since these have to be closed during mould filling and polymerisation of the matrix, it is essentially a blind process. Fibre Bragg gratings (FBG) constitute an attractive solution to monitor RTM processes due to advantages such as: the small size of fibre sensors similar to glass fibre; possibility of creating long strands of fibres with multiple sensors (up to 20 sensors) and linking various fibres in a multiplexed system (spatial multiplexing techniques). These sensors, capable of measuring strain, pressure and temperature, provide high feedback speeds with accurate results, making this an attractive sensing technology. Another potential use for this system is the non-destructive evaluation of

components in service conditions[3,4].

The main purpose of the present work is to demonstrate the reproducibility and reliability of the experimental results obtained in the monitoring and control of RTM process. This research meant to evaluate the performance of FBG sensors in monitoring and control the mould filling and curing of the thermoset matrix in the entire cavity of the mould.

2. EXPERIMENTAL WORK

2.1. Materials and Sample Dimensions

For the following experiments a rectangular mould with a 645×340×5 mm^3 cavity was used. A radial injection was performed, from an injection port at the centre of the cavity. Two additional vacuum points were located at the periphery of the mould to assist the injection.

The raw materials were: a polyester resin from NESTE™, with low viscosity; a reinforcement sandwich material, Rovicore® from CHOMARAT™, with glass fibre skins and a synthetic non-woven PP core.

2.2. Experimental Set-up

The system proposed and developed for monitoring and control RTM processes is presented in figure 1. This system consists in a rectangular mould to produce composite laminates, an erbium broadband optical source (Photonetics FIBERWHITE) to illuminate the sensors, an optical spectrum analyser (ANDO AQ6330) to measure the Bragg wavelength shifts, a 3 dB coupler to separate the reflected signals form the FBG sensors and a computer data acquisition system (LabView™) for flexibility in data display, processing, and storage.

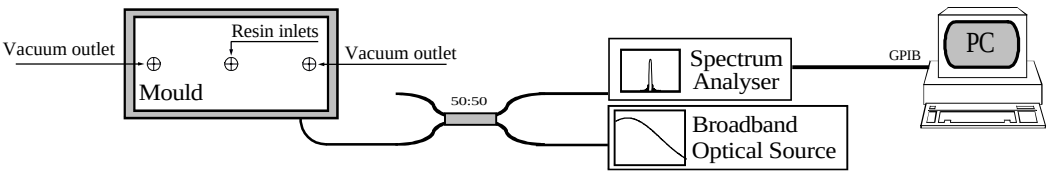

Figure 1. Experimental set-up used for monitoring RTM process.

The FBG sensors are simultaneously sensitive to strain (through the physical elongation of the sensor and the change in fibre index due to the photoelastic effect) and temperature (arisen due to the inherent thermal expansion off the fibre material and the temperature dependence of the refractive index). The procedure used to separate these parameters was to insert a FBG sensor in a capillary tube providing suitable isolation from strain and therefore measure only temperature (see figure 2). The capillary tubes used had ∅1.3 mm and the optical fibre has ∅0.125 mm.

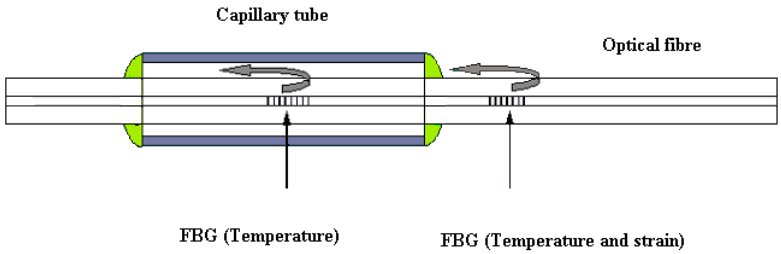

Figure 2. Temperature and temperature/strain FBG sensors.

The experimental work to monitor and control the RTM process consisted in two different experiences. In the first experience (experience type 1), the optical sensing was defined by two temperature Bragg grating sensors in an optical fibre. The location of sensors inside the mould was defined in order to allow comparison of values when resin reaches the sensors and polymerisation occurs. In the experimental set-up illustrated in figure 3, FBG_1 and FBG_2, with λ_{B1}=1561 nm and λ_{B2}=1557 nm (see figure 4), are approximately at the same distance from the injection point.

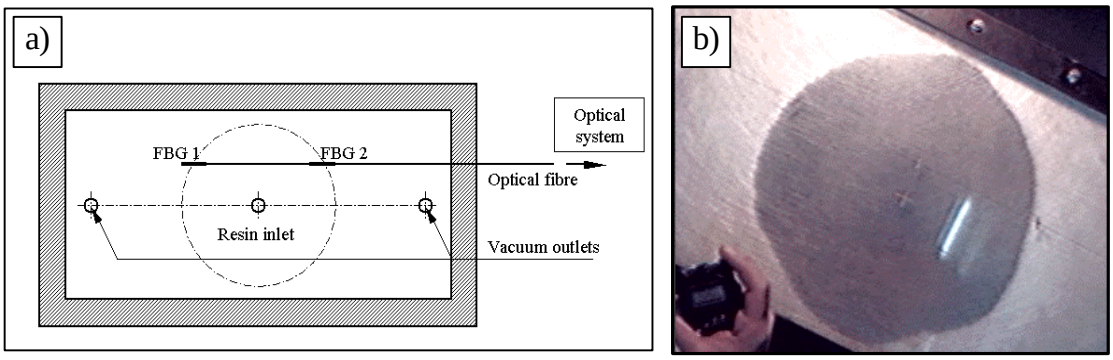

Figure 3. a) Location of the sensors inside the mould, FBG_1 and FBG_2.
b) Resin front progression during mould filling-up operation.

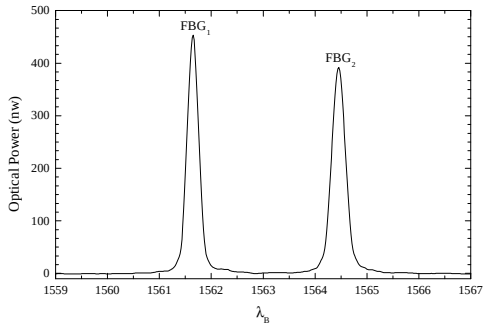

Figure 4. FBG_1 and FBG_2 spectral response (λ_B – wavelength)

In the second experience (experience type 2), nine temperature sensors were distributed around all cavity mould to show if the resin reaches every points of the cavity and the preform is well impregnated. Furthermore, it is possible to obtain the temperature profiles during cycle production. Figure 5 illustrates the experimental set-up. The location of sensors allows comparing results between FBG sensors, FBG 2, 3, 5 and 6 that are at the same distance from the injection point, as well as FBG 1 and 4 and FBG 7, and 9.

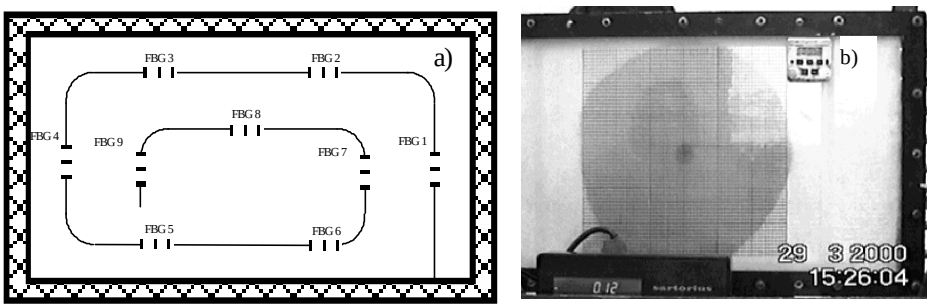

Figure 5. a) Different location of the sensors inside mould.
b) Flow front progression during resin mould filling.

2.3. Experimental Results

The experimental procedure is the same for all experiences. Two layers of the reinforced material are laid down on the mould with the optical fibre, containing the FBG sensors, between them. After that, the mould is closed and the resin is prepared for radial injection. The catalysed resin (at room temperature) is put inside a pressure pot that is regulated to $1.5x10^5$ Pa. A vacuum apparatus is applied to the mould giving $0.5x10^5$ Pa. The injection begins, first with the opening of the vacuum ports and, after few seconds, the resin port. After injection each port is closed and the optical system registers the polymerisation of the matrix.

2.3.1. Experience Type 1

The experience type 1 consists in two injections. Initially, the experience is limited to monitoring with the mould at room temperature, and in the second injection monitoring and process control are performed with the mould heated at 50ºC, before resin injection.

2.3.1.1. Monitoring RTM Process

Figure 6 shows the temperature variations due to mould filling during resin injection. The temperature of the cavity was 19ºC and the resin was injected at 14.5ºC. When the vacuum ports were opened (point A) the sensors detect the pressure variations. Injection begins at point B, the temperature starts to decrease due to the temperature of the resin, which is lower than the temperature of the mould. The flow front progression is detected, at each sensor, at points C1 and C2. The mould is completely full after 100 seconds (since the optical system was switched on).

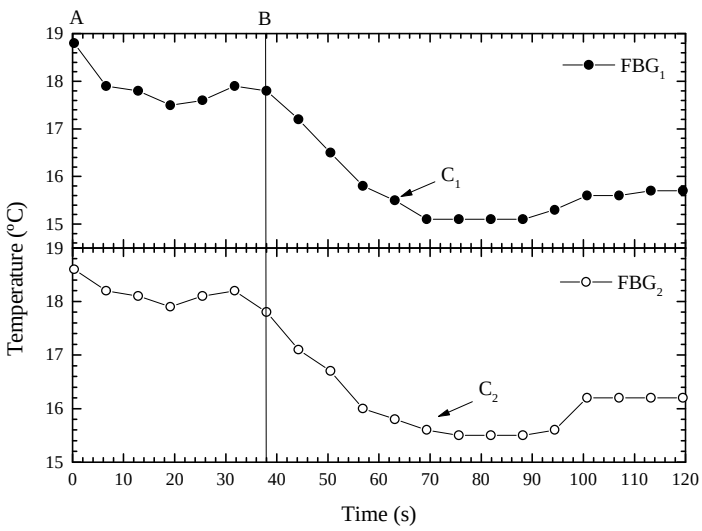

Figure 6. Temperature variations due to mould filling during resin injection:
A) Vacuum inlet; **B)** Resin injection; **C_1)** and **C_2)** Resin arrival at FBG_1 and FBG_2.

Figure 7 presents the temperature profiles during the same production cycle. Zone C, shows mould filling and point D is the exothermic peak when maximum temperature occurs and polymerisation of the matrix is completed. The time since injection till maximum temperature is approximately 90 min.

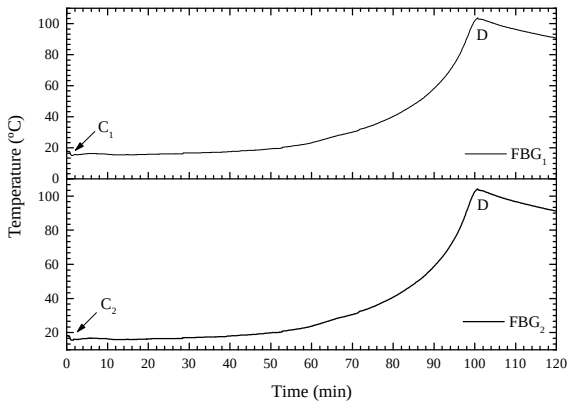

Figure 7. Temperature profiles during cycle production:
C_1) and **C_2)** Mould filling during resin injection; **D)** Exothermic peak.

2.3.1.1. Monitoring and Control of RTM Process

In the following experience, the production parameters were the same but now the mould was preheated to accelerate the polymerisation of the matrix. In figure 8, it is possible to observe the temperature profiles of the matrix in the entire cavity. The mould temperature is approximately 50ºC (till point A), after the mould attained the temperature desired then the

vacuum is opened (between points A and B) and the resin is injected at 14ºC (point B). Temperature begins to decrease as resin is injected due to the lower resin temperature and ends with the mould completely filled (between points B and D). The progression flow front is detected at FBG sensors (point C).

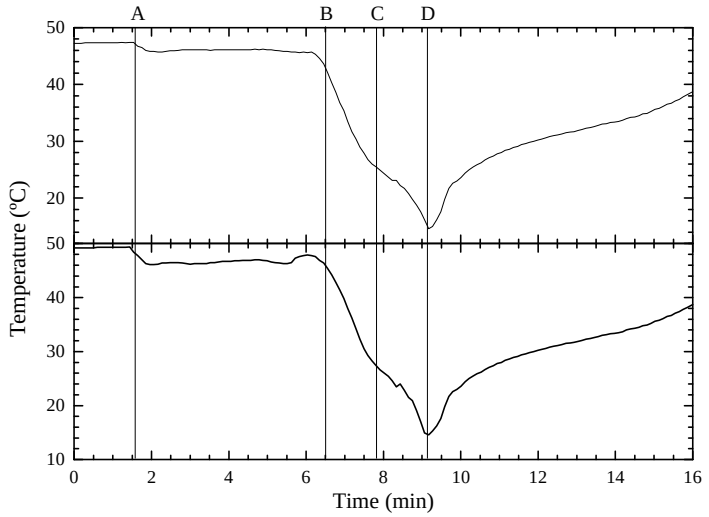

Figure 8. Mould filling during resin injection.
A) Vacuum inlet; **B)** Resin injection; **C)** Resin arrival at sensors; **D)** End of resin injection.

The temperature profile during cycle production is presented in figure 9. After injection, the temperature of the resin begins to increase, due to the mould heat transfer, following the exothermic reaction (point E). The time since injection till maximum temperature is approximately 16 min.

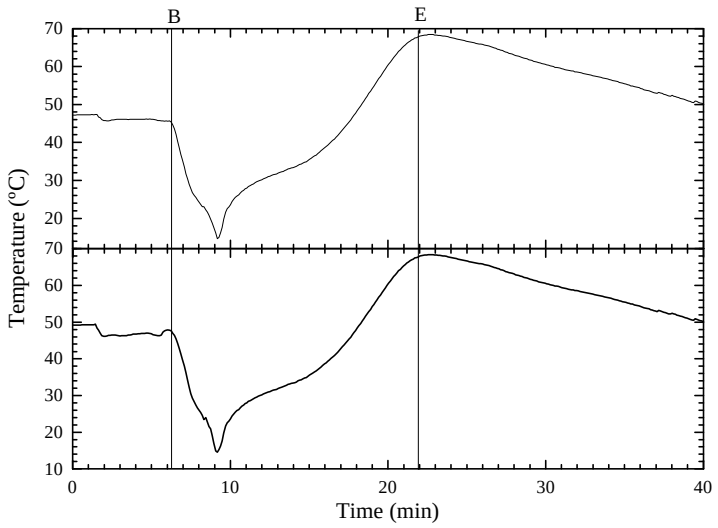

Figure 9. Temperature profiles during cycle production:
B) Resin injection; **E)** Exothermic peak.

2.3.2. Experience Type 2

The results of the following injections, with nine temperature FBG sensors, demonstrate that the resin arrives at different times at each sensor and the exothermic reaction of the resin does not happen at the same time in the entire cavity. In the second injection the mould was preheated to accelerate polymerisation.

2.3.2.1. Monitoring RTM Process

Results presented in the following paragraphs were obtained using the experimental arrangement shown in figure 5.

Figure 10a) shows the analysis of temperature variations during resin front progression. In zone I, sensors measured ambient temperature. In zone II, vacuum was detected as a small decrease of temperature in all sensors except in the one located near the injection point (FBG 8). Few seconds later, resin at 15ºC was injected in the mould using a pressure of 2×10^5 Pa and assisted with vacuum of 0.6×10^5 Pa, while its progression was detected through an increase of temperature in each FBG sensor. The injection time was 40 seconds and when it was completed, the vacuum and injection ports were closed. In zone III, the temperature decreases and becomes stable.

Figure 10b) shows the exothermic reaction of the matrix. The time since injection till maximum temperature is approximately 80 min. The exothermic peak range from 80 to 100ºC, clearly defined in zone IV. In zone V, the reaction was finished and temperature decreased to ambient temperature.

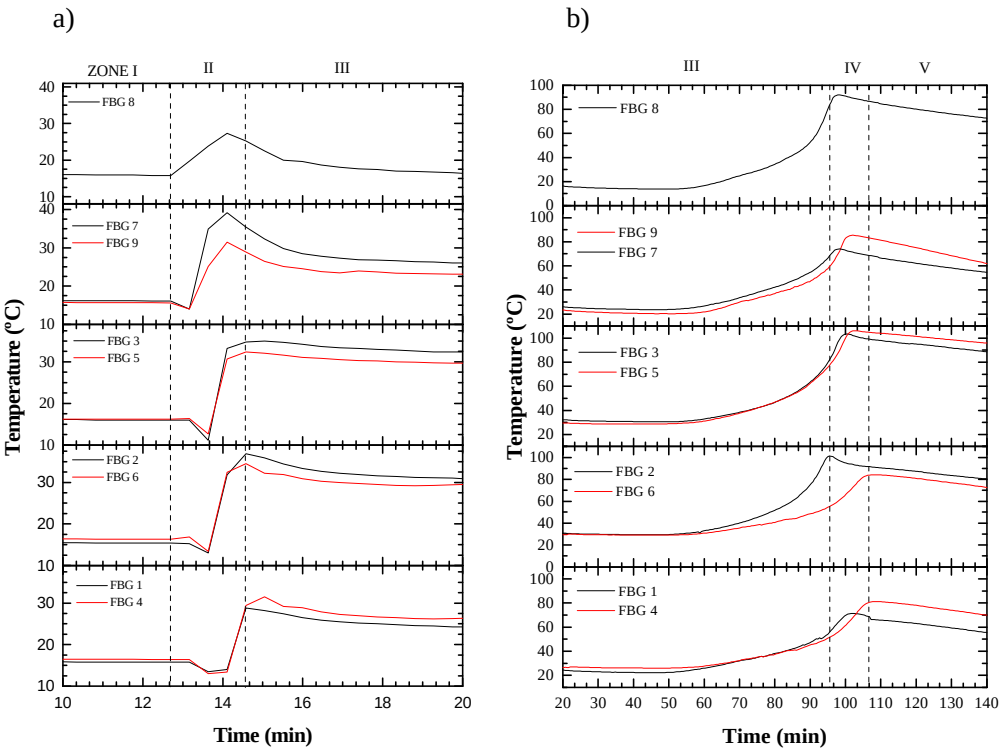

Figure 10. a) Temperature profile of resin front progression.
b) Polymerisation reaction of the resin.

2.3.2.2. Monitoring and Control of RTM Process

In the following experience the sensor nearest to injection point was removed and FBG 7 and FBG 8 were placed close to injection point and nearly at the same distance from it. The other sensors maintained the location. Figure 11 presents the temperature analysis during monitoring and control of the process. The mould was preheated at 42ºC (zone I). The resin was injected at point A (beginning of zone II) and arrives at sensors in point B. The mould heat transfer to laminate accelerates the exothermic reaction of the resin and the maximum temperature occurs at point C. The time since injection till maximum temperature is approximately 14 min. As soon as the exothermic peak is reached the mould is cooled through a thermo regulator (zone III) with cold water.

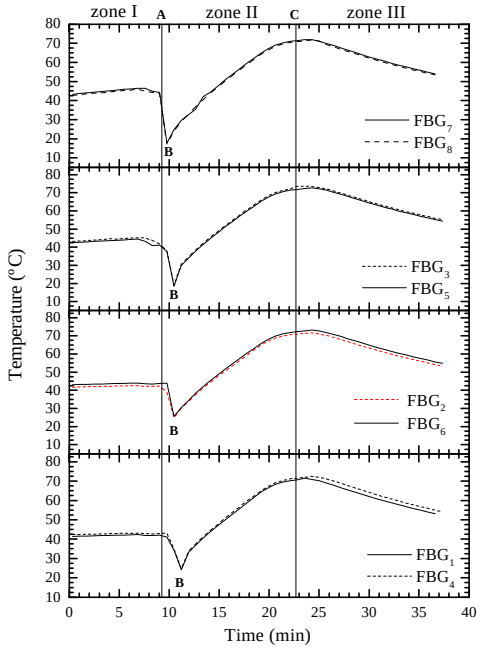

Figure 11. Temperature analysis of the resin front progression.

3. DISCUSSION OF RESULTS

The procedure used to measure temperature, by introducing the FBG sensor in a capillary tube, allowed the detection of resin front progression and the degree of polymerisation. For composite structures with large dimensions the temperature profiles offers a great advantage. Through its analysis, it is possible to detect the presence of the resin in all sensors and consequently to know that the mould is completely filled. Other advantages are related with the determination of the degree of polymerisation, in the whole structure, from the exothermic peak, and also allowing the definition of the right time to demould, when the sensors indicate that correct temperature is reached.

The results of the experience type 1 clearly demonstrate all different phases of the cycle production. The reinforcement used was isotropic so it was expected that sensors, located at the same distance from injection point, had similar results. In the first injection, the time since

beginning of injection till exothermic peak was approximately 90 min and in the second injection was approximately 16 min. Consequently, the use of temperature FBG sensors allowed to define the right time to heat and cool the mould in order to accelerate the exothermic reaction of the matrix and reduce cycle production.

In a similar way, the results of the experience type 2 also illustrate the presence of flow front in different locations of FBG sensors. The exothermic reaction does not happen at the same time in all points of the mould cavity; the exothermic peak occurs firstly near injection point following the points at longer distance from it. The monitoring and control experience present results more similar due to mould heat transfer in which the development of temperature is more uniform. In the first injection, the time since beginning of injection till exothermic peak was approximately 80 min and in the second injection it was approximately 14 min.

4. CONCLUSIONS

The understanding of different measurement performed is essential to obtain accurate results from experiments. In previous works[5,6] the sensor etched at the extreme of optical fibre and near injection point revealed different measurements. The experimental work done so far permit to conclude that strain measurements depend not only of vacuum and pressure sensitivity but also on the location of sensors in the optical fibre.

The experimental results illustrate that FBG sensors are able to monitor and control the manufacturing process. During cycle optimisation the temperature FBG sensors are preferable as they offer more data about the variables of RTM process. The strain/temperature FBG sensors[5] are more sensitive to vacuum and pressure variations and its location than temperature FBG sensors, assembled into capillary tubes. However, the strain/temperature FBG sensors are more practical to handle and adequate to monitor the mould filling and moreover to monitor the structure in service.

The present experiments added more value to this research work since it allowed to define the right time to heat and cool the mould in order to accelerate matrix polymerisation and reduce cycle production with success.

In composite components with larger dimensions the temperature analysis is important to consider because it allows a better understanding of the process. This is possible because nine sensors could be integrated in the mould without affecting the normal evolution of the RTM process. In contrast, the utilization of traditional thermocouples would require the mould to be machined, compromising the sealing of the mould. In addition, if multiplexing techniques are further considered, a larger number of sensors could be used to monitor more complex and extensive components.

In conclusion, it was demonstrated that FBG sensors present a great advantage to composite production since they allow the detection of different phases during the manufacturing process. Another potential benefit results from the utilization of these same sensors in post-fabrication monitoring of the component in service.

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REFERENCES

1. Rudd, C D, Long, A C, Kendall, K N and Mangin, C G E "Liquid Moulding Technologies Resin Transfer Moulding, Structural Reaction Injection Moulding and Related Processing Techniques", *Woodhead Publishing Limited, Cambridge*, England, 1997.

2. Simpson, J.O, Wise, S. A, Bryant, R. G., Cano, R. J., Gates, T. S., Hinkley, J. A, Rogowski, R. S., and Whitley, K. S., "Innovative Materials For Aircraft Morphing", *NASA Langley Research Center, SPIE'S 5th Annual International Symposium on Smart Structures and Materials*, San Diego, CA, pp. 10, 1998.

3. Kersey, A.D., Davis, M.A., Patrick, H.J., LeBlanc, M., Koo, K.P., Askins, C.G., Putnam, M.A., and Friebele, E.J. "Fibre Grating sensors", *J. Lightwave Technol.* Vol. 15,n. 8, pp. 1442-1463, 1997.

4. Morey, W.W., Meltz, G., and Glenn, W.H., "Fibre optic Bragg grating sensors", in *Fibre Optic and Laser Sensors VII*, Proc. SPIE 1169, Boston, USA, pp. 98-107, 1989.

5. C. Novo, O. Frazão, A. N. Costa, A. Vieira, N. Correia, F. M. Araújo, I. Dias, A. T. Marques, "Flow Front Monitoring in RTM Process Using Fibre Bragg Grating Sensors", SAMPE EUROPE 2001, 22nd International Conference, Paris, France.

6. C. Novo, O. Frazão, A. N. Costa, A. Vieira, N. Correia, F. M. Araújo, I. Dias, A. T. Marques, "Progression Monitoring of the Flow Front in RTM Process Using Fibre Bragg Grating Sensors", OFS 2000, 14th International Conference on Optical Fibre Sensors, Venice, Italy.