On-line monitoring of a laser-assisted fiber placement process with CFR thermoplastic matrix by using Fiber Bragg Gratings

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Abstract
Manufacturing processes based on monitoring techniques with different kind of sensors have increasingly been under study and implementation due to the guarantee of improving project quality, effectiveness and costs. Fiber Bragg Grating (FBG) sensors have been traditionally developed for Structural Health Monitoring (SHM) technology with the future aim of being incorporated in aeronautical structures while informing about in-service health state for avoiding possible failures as well as for optimizing costs. In recent times, FBG’s and other sensors have been used in manufacturing processes during the production of composite materials parts to develop the on-line monitoring technology. Its use allows monitoring several of the process parameters in real-time which are directly related with the mechanical and physico-chemical properties of the final structure. This research includes the activities carried out with the goal of process monitoring in composites while manufacturing panels with continuous carbon fiber reinforced thermoplastics by automatic lamination and in-situ consolidation (ISC) technique. The process is based in the fusion bonding between two layers of material preheated by a laser thermal source and placed in contact by applying pressure with an elastomeric compaction roller. Works involved in these studies consist of embedding fiber optics based on FBG during lamination and consolidation of a structure while executing the placement in order to monitor both the thermal profiles developed in the material and the deformations experienced.

The obtained information by these measurements permits to compare data with other standard sensors as well as evaluate the effect of residual stresses generated during the process.

Keywords: Thermoplastics, Process monitoring, on-line monitoring, Fiber Bragg Grating

1. INTRODUCTION

Carbon Fiber Reinforced Thermoplastics materials have been widely under research in last decades within the automotive, aeronautical and aerospace sectors due to their benefits compared to the traditional thermosetting matrixes composite materials. Thermoplastics matrixes as polyetheretherketone (PEEK), polyetherketoneketone (PEKK) or polyphenylene sulfide (PPS) can improve the properties in the final composite parts such as better mechanical performance; lower water absorption; better chemical and impact resistance, infinite shop life, in addition to reparable and reprocessing possibilities [1].
Besides, composite manufacturing processes are oriented to reformulate the standards process in order to reduce fabrication costs and times; coming from the autoclave mainly. Thermoplastic resins are a solid option for alternative manufacturing processes due to the fact that no chemical reaction and curing time are required for their processed. Melting and consolidation is only required.

Stamp moldings, thermoforming, vacuum bag in oven or autoclave compose the thermoplastic manufacturing processes nowadays, including electrical resistance, ultrasonic and induction welding as joining technologies. But these processing methods have several barriers for the automatization and adaptation in the aeronautical industry.

That is the reason why Automatic Fiber Placement (AFP) machines with In-Situ Consolidation (ISC) (Figure 1) systems are under development in composites materials industry while ensuring the same mechanical properties and behavior of the materials [2, 3]. This technique is based in a head-machine which places impregnated material in a tooling while a heat source is heating the material above its melt temperature. Pressure needed for the consolidation of the material and the voids removal is applied by a compaction roller.

FIDAMC has carried out advances in thermoplastic laser-assisted automatic tape laying since 2010 and it is still under development with the aim of producing integrated structures, curved parts in addition to control and optimize the process [4-6].

![Figure 1. Temperature impact on process (left) Set up for ISC process monitoring (right)](image)

The process of ISC is not obvious, and involves a series of physical phenomena that are required to be understood and interpreted. Thermal history and heat transmission appears as fundamental parameter which domains the process and it is required to be understood and interpreted to assimilate the nature of the process for their optimization. Thermographic camera is nowadays used to monitor the temperature profiles and thermocouples and Fiber Bragg Grating sensors are required for the correlation and process control.

Phenomena as intimate contact, crystallization or residual stresses also need to be understood to lead ISC technique to levels of high production and effectiveness.

Besides, these events may lead to the appearance of defects such as lack of consolidation or residual strains due to the nature of the process itself. Differences between the theoretical and
Final dimensions of the composite manufactured parts are caused by the appearance of residual stresses in the process.

Fiber Bragg Grating (FBG) sensors appear as the best candidate to monitor the process parameters as a powerful tool to understand the process. FBG sensors in aeronautical industry are commonly investigated and used in Structural Health Monitoring (SHM) with the goal of monitoring the performance of the aircraft structure and knowing the health of the structure in real-time. FBG sensors are incorporated to the ISC process (Figure 1).

Although the FBG sensors have been traditionally used for in-service monitoring, the interest of the research centers for process monitoring has been clearly increasing in the recent times: Resin flow in Resin Transfer Moulding (RTM), degree of curing in autoclave cycle or residual stresses in press manufacturing are some examples of parameters and processes which have been under research [6-8].

Furthermore, quality controls are increasing in the aeronautical field with the development of new technologies and materials so that new ISC manufacturing processes must reach a high level of effectiveness, productivity and a low level of manufacturing associated defects to accomplish the aerospace parts criteria. Industry is being led to the more commonly named industry 4.0 or smart industry which consists in a superior step in automatization, process controlling where internet of things, big data and sensors will take a relevant paper. The inclusion of FBG sensors in manufacturing processes leads the industry one step closer to detection of defects in real time during the process.

This paper shows that FBG sensors have been successfully incorporated at the ISC process. FBG has satisfactory monitoring of the thermal and strain profiles. Conclusions from residual stresses have been found. Once the embedding is optimized, the obtained results are essential for understanding the physics of the process and to use the FBG sensors as alternative control system of the process in addition of thermocouples and thermography.

Two different experiments have been performed with a Micron Optics® SM 130 dynamic optical interrogator. The first test is carried out by embedding a simple FBG sensor and a thermocouple to monitor the consolidation experiments. The FBG sensor will be affected by temperature and strain simultaneously and both effects will be decoupled with the thermocouple measure of temperature. The second experiment consists in a double FBG optical fiber where one of the sensors has been isolated from strains. This way, thermocouple is not required to perform the decoupling of the strain and temperature effects monitored.

2. FBG BASING PRINCIPLES

A FBG sensor is located inside a single-mode silica optical fiber and it has been created by imprinting periodical patterns within the optical fiber core with the light of a laser-beam striking the core through a grating. The ultraviolet light from the source causes a periodic perturbation in the refractive index in the fiber core along several millimeters of the length of the optical fiber. The FBG sensor has been created.
When the optical fiber is connected and illuminated by a broadband source, the light will be strongly reflected back in the FBG (Figure 2) at the Bragg wavelength $\lambda_B$ according to the expression:

$$\lambda_B = 2n_e \Lambda$$  \hspace{1cm} (1)

Where $\Lambda$ is the grating period and $n_e$ is the effective index of refraction.

The basic principle of the FBG sensors is to monitor the shifts of the reflected Bragg wavelength. Any future environmental perturbation that interacts with the optical fibre will cause a change in the index of refraction as well as a change in the received wavelength (Figure 2) because the the periodic spacing between the grating planes has been modified by the alteration in the media. FBG optical sensors are developed to monitor phenomena such as strains, temperature, vibration or pressure; being strains a temperature the parameters which are usually monitored in the manufacturing composite processes.

![Figure 2 FBG sensors principle (left). Wavelength shift due to strains (right)](image)

When an external distortion corresponding to a mechanical or thermal distortion is interacting with the FBG sensor and the optical fiber, the effective refractive index changes involving a wavelength shift.

$$\Delta \lambda_B = \lambda_0[(\alpha + \xi)\Delta T + (1 - p_e)\Delta \varepsilon] = k_e \Delta \varepsilon + k_T \Delta T$$  \hspace{1cm} (2)

As it can be seen in Eq.2 the wavelength shift is directly proportional to changes in the strain or the temperature which is felt by the FBG sensor. In the equation $\Delta \lambda_B$ corresponds to the wavelength shift; $\alpha$ is the coefficient of thermal expansion of FBG; $\xi$ is the Bragg grating’s thermos-optical coefficient, $p_e$ is the photoelastic constant of the fiber; $\Delta T$ is the change of the temperature and $\Delta \varepsilon$ is the strain change. In the second part of the equation, the expression is simplified by grouping the different parameters into $K_e$ and $K_T$: which are the sensitive coefficients of the strain and temperature, respectively.

Temperature and strain must be decoupled when both phenomena are occurring at the same time. It could be separated by means of knowing the temperature of the process at real time while monitoring the strain in the process. Eq.3 is used to decouple strain and temperature.
which are monitored by the same FBG sensor.

\[ \Delta \varepsilon = \frac{\Delta \lambda_D - K_T \Delta T}{K_e} \]  \hspace{1cm} (3)

In the experimental method, the experimental expressions that can be found in much bibliography [9] are used and inserted into the used software. Compensation of the temperature by separating the effect of the temperature and the strain in the wavelength shift will be achieved by two different techniques and correlated between them.

### 3. EXPERIMENTAL METHOD

This study is based in the incorporation of FBG optical sensors for real time monitoring of strain and temperature profiles that are taking place at thermoplastic processed by means of Automatic Tape Placement with a laser-assisted In-Situ Consolidation (Figure 3).

Two different FBG configurations (Figure 4) are tested to validate the functionality of the FBG sensors for strain and temperature on-line monitoring at in-situ consolidation process.

The specimens in the experiments are Carbon fiber/PEEK composites manufactured using APC2-AS4 material from Cytec®, unidirectional prepreg material which consists of a Polyether ether ketone (PEEK) matrix with carbon fibre AS4 as reinforcement. The temperature of the process is 400°C. The monitored specimens in the tests consist in a stacking of 10 plies taped by the ATP machine one by one, consolidating each tow on the previous ply. Pressure is then applied by the compaction roller moved by the head machine. Tows are 6.35mm width. Final geometries of the specimens are 300x6.35x1.35mm.
In the 1\textsuperscript{st} experiment a fiber optic with a simple FBG sensor centered in a $\lambda_B$ of 1557.5 nm and 10 mm length is embedded between the 1\textsuperscript{st} and 2\textsuperscript{nd} ply of the stacking. A thermocouple is located with major proximity to the FBG sensor to monitor the temperature as close as possible to the FBG sensor. In this way, the temperature is monitored by both sensor and thermocouple while strain variations are also recorded at the FBG sensor. The temperature and strain combined effects on the sensor will be later decoupled by knowing the temperature with the thermocouple.

In the 2\textsuperscript{nd} experiment a fiber optic with two 10mm length FBG sensors centered at $\lambda_B$ of 1548.0 and 1556.8 nm respectively are embedded between the 1\textsuperscript{st} and 2\textsuperscript{nd} ply of the 10 plies stacking. One of the sensors is located at the end of the optic fiber has been encapsulated within a brass cylinder to make that sensor being isolated to the strains effects (Figure 5).

A thermocouple is also located next to the encapsulated sensor to validate both measurements of the temperature profiles.

Results from proposed experiments will be first used to validate the proper embedding of FBG sensors in the automatic tape laying of high temperature thermoplastic materials due to the fact that high temperatures and pressures are reached during the process. A comparison between the results of both tests are compared later for the validation of the use of FBG sensor technology for on-line monitoring of strain and temperature profiles which occurs while the thermoplastic part is under manufacturing.
4. RESULTS

On-line monitoring of the process has been similar in both experiments. Data acquisition starts when the 2nd ply is placed and the system is continuously monitoring during the taping of the 10th (last) ply.

Results of the wavelength shift in the 1st experiment (with one FBG) is shown in Figure 6.

![Figure 6. FBG wavelength shift monitored at 1st experiment](image)

Peaks correspond to the time when the FBG sensor is irradiated by the heat source and deformed by the compaction roller. Maximum values are directly attenuated with the number of stacked plies and it must be taken into account that after stacking of every ply, the value of the wavelength does not come back to the same level, staying in a altered level. This effect is relevant it has been perceived as residual strain effects inherent to the nature of the process.

As commented in episode 3, temperature is monitored during the process by the thermocouple. A data post-processed of results shown in Figure 6 is done to decoupling the effects of both temperature and strain monitored by the FBG sensor. In this way, strain and temperature profiles occurring during the laser-assisted ATP process is shown in Figure 7.

![Figure 7. Temperature registered by the thermocouple (left) and strain profile after decoupling (right)](image)
Temperature data is transformed into wavelength shift via analytical expressions, and then subtracted to the total wavelength shift in order to obtain the strain profile taking part in the process. First temperature peak is remarkable higher than the temperature that is expected to be irradiated on the sample. It could be due to the directly contact of the laser emission with the thermocouple metal. The first peak has been removed to calculate the strain profile.

The monitored results of wavelength shift during the 2\textsuperscript{nd} experiment are shown below. In this case, the test is performed with 2 FBG sensors but only the recorded data by the naked sensor (not recovered with brass cylinder) is shown in Figure 8.

![Figure 8. FBG wavelength shift monitored at 2\textsuperscript{nd} experiment](image)

Peaks are attenuated with the subsequent stacking of the plies and the initial position is not recovered after the 2\textsuperscript{nd} ply is located and consolidated.

Temperature is monitored in two ways in this experiment: thermocouple and FBG sensor which is strain isolated is only affected by temperature changes in its surrounding. Both temperature registers are shown in Figure 9.

![Figure 9. On-line monitoring of Temperature profiles](image)

It can be deduced from the results that FBG sensor is monitoring higher temperatures than the thermocouple, attending to the registered data. It is happening due to the different diameters of the devices as it can be seen in Figure 10 where encapsulated FBG cover the section of a higher number of plies than the thermocouple, reason why FBG temperature monitoring starts to attenuate later than the thermocouple. Same results are found in [10].
In experiment 2 the strain profile could be decoupled in two different ways: with the aid of the temperature registered by the second FBG or the thermocouple. Both results are exposed in Figure 11.

5. CONCLUSIONS

Two CF/PEEK specimens have been manufactured by laser-assisted Automated Fiber Placement with in-situ consolidation technique. FBG sensors have been successfully embedded in the samples. Sensors have monitored the high temperature process of PEEK consolidation.

The obtained results indicate that FBG sensors can be satisfactory used to monitor the thermal profile of the process. Induced temperature and strains have been successfully monitored with a single and two FBGs sensor. Strain and temperature effects have been decoupled with one thermocouple and/or with a secondary FBG isolated from strains. Results have been correlated. Differences in temperature measurements between FBG and thermocouple will be solved by adjusting the encapsulated sensor.

Analysis of the results lead to consider FBG as a good mechanism to visualize effects of residual stresses generated during the process since its effect is observed in the wavelength shift.

Future works will be focus in the use of FBG sensors for the monitoring of effects of the manufacturing defects in real-time.
REFERENCES