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On-Line Process Monitoring for Aero-Space Components Using Different Technologies of Fiber Optic Sensors During Liquid Resin Infusion (LRI) Process †

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Abstract: The FLASH-COMP project aims to introduce novel inspection and monitoring technologies to develop a digital solution to predict defects during manufacturing, aiming to reach a zero-waste approach in composites manufacturing. Particularly, it's studied the integration of two different Fiber Optic Sensor (FOS) technologies: Fiber Bragg Grating (FBG) and distributed All Grating Fiber (AGF®), to retrieve relevant data during the preforming stage and later resin infusion process for aero-space materials. During the study, both FOS technologies were introduced into the materials, varying process conditions and the introduction of some artificial defects to evaluate the sensors response to correlate them after with their signals. Both systems can retrieve relevant information during the process such as vacuum, leaks and temperature changes, presence of voids and air bubbles, detection of dry zones, and resin flow monitoring. Further developments have to be focused on the scalability in the implementation, since FOS are fragile to handle and need specific training to use it in a more industrial field.

Keywords: FOS; process monitoring; manufacturing

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1. Introduction

Greener and lighter manufacturing solutions are needed more nowadays, aiming to reduce the amount of waste that main sectors are producing, particularly in the composites industry. Liquid Resin Infusions (LRI) process is widely extended due to its capabilities on producing high-performance materials at a lower costs, compared to traditional method as autoclave [1]. Despite its advantages, quality control and sample inspection are still being carried once the manufacturing has been performed, being necessary to apply correction afterwards or discarding the component if this cannot accomplish the quality expected for it, generating waste.

Integrated systems as Fiber Optics Sensors (FOS), have been implement mainly to structural health monitoring (SHM) and process monitoring, giving capabilities on resin flow following, deformations, temperature, curing process and failure monitoring [2–4]. Previous works demonstrated that FOS can give relevant LRI process information such as

temperature variations, vacuum level and leaks, dry zones and porosity, and resin flow front evolution [5].

The main objective of the FLASH-COMP project [6,7] is to develop a fast and reliable (FLASH) human-oriented quality control solution capable of identifying in a timely-manner defectiveness during process and, consequently, to determine the in-situ corrective actions to be implemented, towards zero-defects LRI manufacturing process, significantly reducing the generation of polymer composites waste. Particularly FLASH-COMP aims to introduce new diagnostic methods to enable real-time process monitoring by giving relevant information during the process without affecting the performance of the final component.

2. Results

2.1. Background

Currently, for liquid composite molding techniques (LCM) as LRI, operators must wait until the end of the process (curing) to determine the quality of the component, bringing risks to the process, aside from time and materials waste. In FLASH-COMP, different monitoring and inspection devices (FLASH-IM) are being integrated into the manufacturing process to gather relevant process data during the infusion and curing stages of the process to: monitor materials behavior, feed simulation models and create data correlation, and lastly, to propose on-line control strategies that will be implemented while the component is being manufactured, aiming to reduce the amount of defects further waste generation (Figure 1).

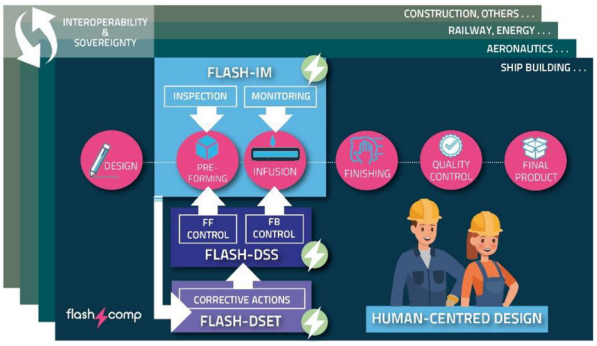


Figure 1. FLASH-COMP approach: implementation of inspection and monitoring systems during the manufacturing process [7].

2.2. Use Case and Technical Developments

FLASH-COMP has two use cases: nautical and aero-space. Particularly, AIMEN's role is to develop one of the FLASH-IM technologies proposed: embedded fiber optic sensors and to carry out its implementation over the aero-space use case.

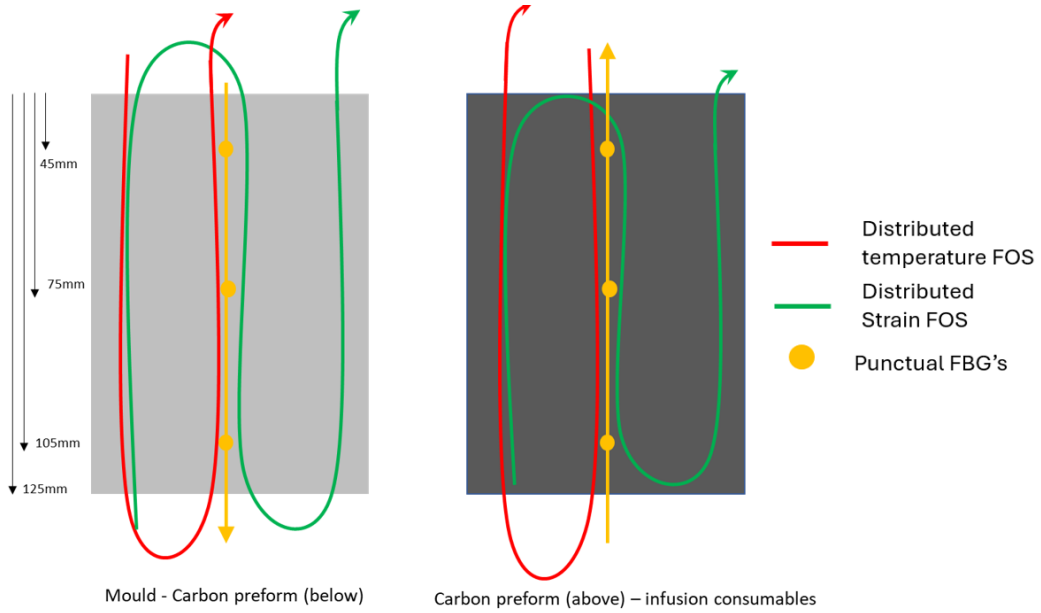
Two main technologies FOS technologies are used: Fiber Bragg Grating (FBG's) and All Grating Fibers (AGF's). FBG's are the type of FS-laser-written (Engionic, Germany) and its data acquisition is performed with an HBM FS22. Selected AGF's are manufactured by FBGS, the interrogator is a SUMMIT Sensurion. Main differences (Table 1) of both technologies are spacing between measuring points, acquisition frequency and cost per length. The objective is to combine both technologies to create a "low-cost" hybrid solution, allowing to integrate specific sensors whenever the amount of data and reliability are needed, reducing the amount of necessary embedded material, to avoid possible interference to the process.

Table 1. Main differences between the FOS technologies for specific use case.

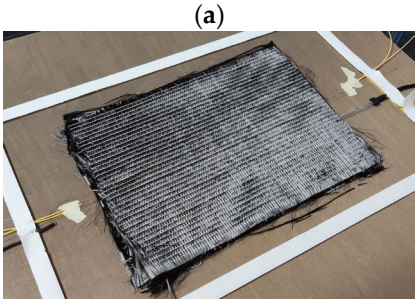
Parameter	FBG's	AGF's
Measurement type	Point sensors (spacing of 4 mm)	Distributed sensors: 1.2–25 mm spatial resolution
Acquisition frequency	1–25 kHz	Up to 60 Hz
Price	20–40 €/sensor	80 €/m

As a main consideration for implementing the embedded sensors during the process, it was determined not to embed sensors inside the laminate, possibly creating local defects and thus, affecting is mechanical performance. Additional focal points were to cover all sample/part length, allowing them to monitor the effect of the resin flow front. Avoid alternations over the surface quality of the component, besides on being solutions easy to integrate and later remove from the final part. With this, we proposed to implement two arrays of FOS layers (Figure 2):

- One in direct contact with the tooling surface
- One in direct contact with the ancillary materials over the laminate



(**a**)



(**b**)

Figure 2. Scheme of the implementation for both FGB's and AGF's in the test sample. (**a**) Maps of the position of the sensing points. (**b**) Real sample.

Both FOS technologies are intended to measure temperature changes and strain deformation (pressure changes) over the samples. With this approach it is possible to monitor both length and thickness of the component.

To be as close as possible to real life conditions, aero-space graded materials were selected: bidirectional NCF carbon SAERTEX 30008799 B-C-606g/m^2-1270mm 0/90 (Castro

Composites, Castellví de Rosanes, Spain). And an aeronautical-grade epoxy resin: Hexcel HexFlow RTM6-2, bi-component version (UNECO. Castellví de Rosanes, Spain); which is mixed and prepared following manufacturer recommendations.

During the preforming stage, FBG's particularly give precise information about the level of vacuum applied over the laminate (Figure 3), even being capable of monitoring vacuum leaks during the process. FOS layers deposited over the tooling surface presented less deformation (minor signals), since the tooling holds main deformation produced by the vacuum bag. While the layer being at the top of the laminate presents more significant signals, possibly giving an idea of the laminate behavior over the sample thickness.

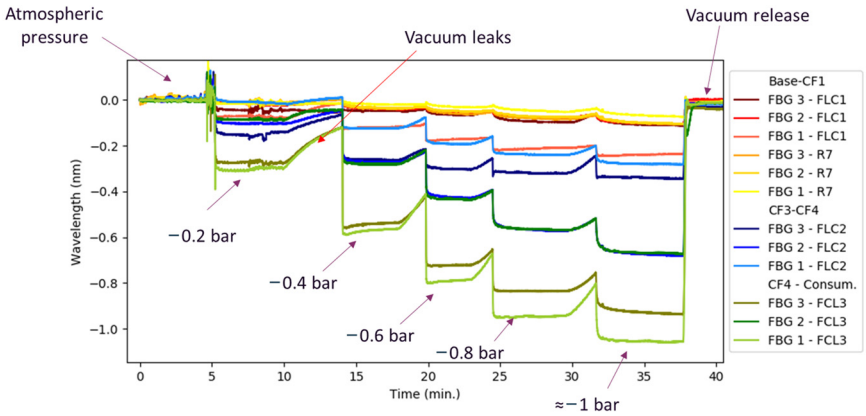
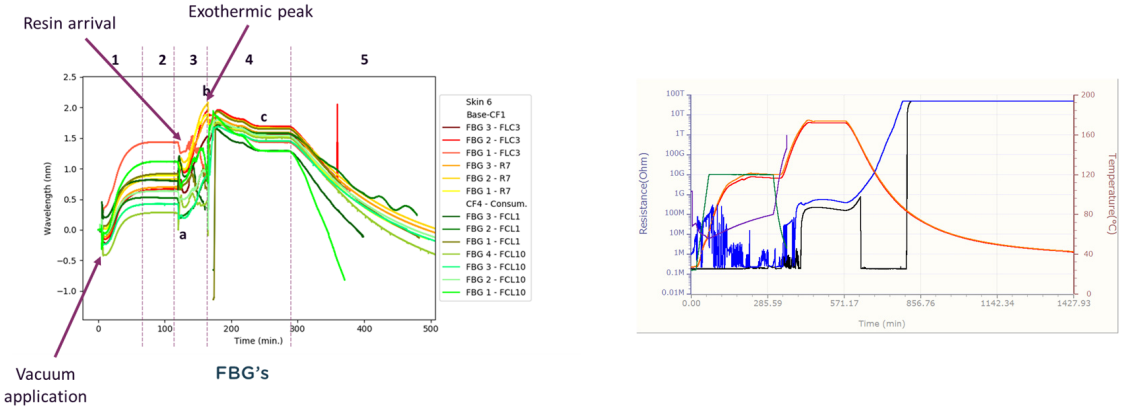


Figure 3. FBG's vacuum and leaks detention during the preforming stage.

FBG's present high sensitivity to local temperature changes during the process. Particularly during the resin impregnation, it is possible to monitor the resin arrival and the exothermic peaks while curing, bringing the possibility to know with precision the moment when the part is ready to be demolded Figure 4.



(**a**) (**b**)

Figure 4. (**a**) Comparison of FBG signals. 1. Heating to infusion temperature (120 °C), 2. Resin infusion and arrival in which the low viscosity point is reached (a), 3. Reaching of cure temperature (180 °C) and point of exothermic reaction (b). 4. Curing stage at constant temperature (c) and 5. Cooling stage. (**b**) Comparison with commercial systems.

AGF's on the other hand are more complex to FBG's, since their signal has more data resolution. Particularly, AGF's can display process information depending on the sample length and process step. One relevant aspect is that, if the AGF's signal is focused on the resin impregnation stage, they can give the exact location of the resin flow front in the preform, as displayed in Figure 5.

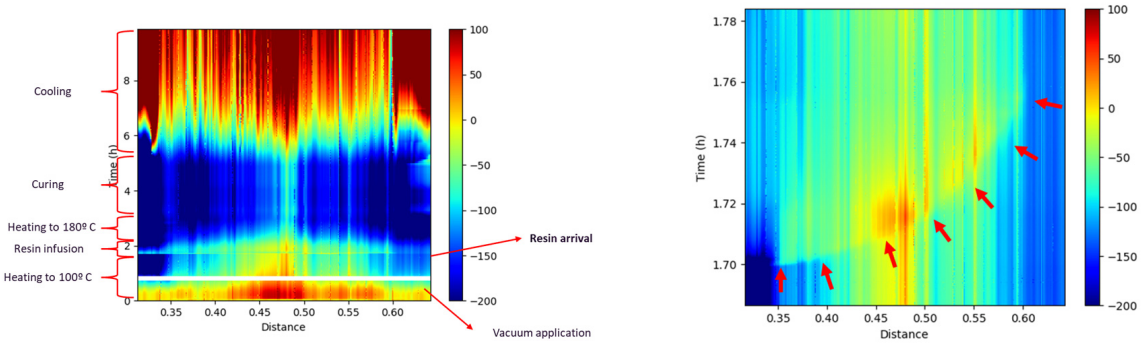


Figure 5. Process monitoring with the AGF's fibers. (**a**) detail of the complete infusion and curing process. (**b**) Resin flow front advancement thought the laminate.

Both FOS technologies allow to display possible defects that the component is having. Vacuum leaks, dry zones or poorly impregnated areas, besides having a temperature follow-up and monitoring in the case of exothermic peaks. An example of this can be seen on the Figure 6, where a dry zone was created to analyze its effect over the FBG's and AGF's, additionally, an example of vacuum leaks during curing can be seen.

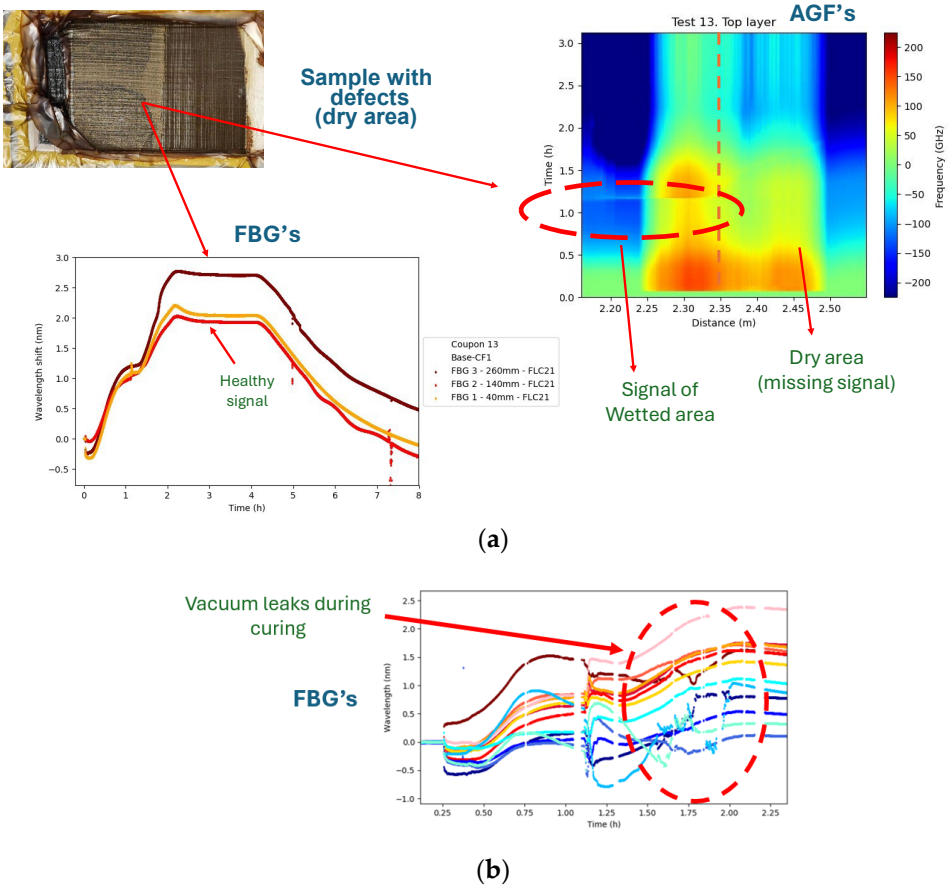


Figure 6. Evaluation of defects using both FOS technologies. (**a**) FBG's and AGF's signal corresponding to a dry area in the laminate. (**b**) FGB signal of vacuum leaks during curing.

Regarding all the capabilities of the FOS, it must be considered that the implementation of both technologies requires a certain skill in order to place them, having care of avoiding breaks into the fibers and the effect of the later vacuum application. Another point is the

surface marks that can leave the fibers in the component, being necessary to avoid possible restrictive zones inside the component to not affect the aesthetics and performance.

3. Concluding Remarks and Next Steps

Both FOS technologies (FBG's and AGF's) are capable to give relevant process information during Liquid Resin Infusion processes. During preforming, precise monitoring to the vacuum levels can be applied, besides having a temperature follow-up. During the resin impregnation, it is possible to monitor relevant process steps such as resin arrival, exothermic peak and curing, even being possible to follow the resin flow front in the fiber preform.

Main technology limits can be summarized as the skills needed to work with FOS technologies, besides on the market price depending on the specific necessities of the technologies. Some advantages and disadvantages can be summarized in Table 2.

Table 2. Advantages and disadvantages of applied FOS technologies.

	FBG's	AGF's
Advantages	Simple and reliable Sensitive to vacuum/pressure levels Sensitive to temperature changes Signals can be compared to traditional sensors (temperature, DC curing)	The fiber is sensitive in all the length (reduce amount sensors needed) Sensitive to vacuum pressure, temperature, resin arrival (estimation of dry zones and resin velocity) Possibility to analyze specific zones for process detailing
Disadvantages	Measurements at specific points (must be defined) to manufacture the fiber	Generation of big amounts of data (storage, treatment) Expensive compared to FBG's

Next steps for the FLASH-COMP work will be focused on: evaluating the scalability of both FOS technologies, while they are being tested on a real-life/complex component, integrating all the FLASH-IM systems into the proposed solution, and validating digital data and simulation ecosystem.

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References

1. ReportLinker, Composites Market Size, Share & Trends Analysis Report by Product, by Resin, by Manufacturing Process, by End Use and Segment Forecasts, 2020–2027. Available online: https://www.globenewswire.com/news-release/2020/08/06/2074010/0/en/Composites-Market-Size-Share-Trends-Analysis-Report-By-Product-By-Resin-By-Manufacturing-Process-By-End-Use-And-Segment-Forecasts-2020-2027.html (accessed on 6 December 2024).
2. Ramakrishnan, M.; Rajan, G.; Semenova, Y.; Farrell, G. Overview of fiber optic sensor technologies for strain/temperature sensing applications in composite materials. *Sensors* **2016**, *16*, 99. [CrossRef] [PubMed]
3. Büyüköztürk, O.; Taşdemir, M.A.; Méndez, A.; Csipkes, A. Overview of Fiber Optic Sensors for NDT Applications. *Nondestruct. Test. Mater. Struct.* **2013**, *6*, 179–184. [CrossRef]
4. Ye, X.W.; Su, Y.H.; Han, J.P. Structural Health Monitoring of Civil Infrastructure Using Optical Fiber Sensing Technology: A Comprehensive Review. *Sci. World J.* **2014**, *2014*, 652329. [CrossRef] [PubMed]
5. Torre-Poza, A.; Pinto, A.M.R.; Grandal, T.; González-Castro, N.; Carral, L.; Rodríguez-Senín, E. Challenges of complex monitoring of the curing parameters in coupons for LRI manufacturing. *Incas Bull.* **2021**, *13*, 203–210. [CrossRef]
6. FLASH-COMP—Flawless and Sustainable Production of Composite Parts Through a Human Centred Digital Approach. CORDIS. Available online: https://cordis.europa.eu/project/id/101058458/results/es (accessed on 29 November 2024).
7. FLASH-COMP: Composite Manufacturing, Right First Time. Available online: https://flashcomp.eu.com/ (accessed on 29 November 2024).

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