A Process for Embedding Fiber Bragg Gratings in Flexible Skin Foils

A. F. Silva[1,*], F. Goncalves[2], L. A. Ferreira[3,4], F. M. Araujo[3,4], P. M. Mendes[1], J. H. Correia[1]
[1] Dept. of Industrial Electronics, University of Minho, Campus de Azurem, Guimaraes Portugal
[2] TMG Automotive, Campelos, Guimaraes, Portugal
[3] FiberSensing, Maia, Portugal
[4] INESC Porto, University of Porto, Porto, Portugal

ABSTRACT

Optical fiber sensors are increasingly used for monitoring purposes, but flexible smart structures based in this type of technology have many industrial applications. This paper explores a new approach for integrating optical fiber sensors in flexible substrates that can be mounted in host structures to monitor. This approach combines two well establish components, Fiber Bragg grating (FBG) sensors and flexible skin-foils. A three-layer foil construction based on the spread-coating process was defined, in which the fiber was embedded in the middle layer. Such disposition ensured protection to the optical fiber element without reducing the sensitivity to external stimulus. The functional prototypes were subject to thermal and mechanical tests, in which its performance was evaluated. The smart structure behaves linearly to temperature cycles by 0.01 nm/ºC and is able to withstand high strain cycles without affecting the measurement characteristics. The obtained results validated this approach. In addition, the flexibility of the explored method allows custom fiber layouts, finishing patterns and colors, enabling this way a range of possible application fields.

Keywords: Optical Fiber Sensors, Fiber Bragg Gratings, Fiber Embedding Techniques, Smart Structures.

1. INTRODUCTION

More than thirty years have passed since the study of optical fiber sensors began and a variety of processes have been explored for different measurands and applications. Nowadays, a few types of optical fiber sensors have reached the market and became a success [1]. In more recent years, optical fiber technology and applications have spread more quickly mainly due to its performance and cost reduction.

Optical fiber sensors have associated a set of advantages such as EMI immunity and high sensitivity, which are becoming key requirements for monitoring solutions. This ensures a distinct edge over the competition. Fiber Bragg gratings (FBGs) and other grating-based devices are examples of the type of sensors which have been in vogue in this last decade [2]. This sensor type has an inherent self referencing signature, allowing sensors multiplexing in a single fiber. FBG sensors are a unique solution specially regarding distributed embedded sensing in materials, known as smart structures. The fibers containing sensing arrays can be embedded into the materials, allowing measurement of parameters such as load, strain and temperature, among other, from which the conditions of the structure can be assessed and tracked on a real-time basis [3]. As they, basically, monitor the structure, they can forewarn abnormalities and prevent failures. Such purpose ensures more working time, less maintenance, better utilization and improved safety, reliability and economy.

However, there is a lack of automated optical fiber integration processes. The development of a generic methodology that offers an integrated breakthrough solution for the industrial manufacturing of flexible optical sensing foils with a wide range of applications is the main goal [4-8]. Subsequently, the development of a flexible substrate or matrix in which FBG sensing elements are integrated in line during the manufacturing process of the substrate itself is aimed. The flexible and stretchable matrix can be sensitive to touch, temperature, pressure, deformation, etc. Such optical sensing structure combines two features of interest: integrated optical sensing and high flexibility.

[*] asilva@dei.uminho.pt; phone: +351-253 510190; fax: +351-253510189

Fourth European Workshop on Optical Fibre Sensors, edited by José Luís Santos, Brian Culshaw,
José Miguel López-Higuera, William N. MacPherson, Proc. of SPIE Vol. 7653, 76533K
 · doi: 10.1117/12.865349

2. FIBER BRAGG GRATING SENSORS

The FBG takes advantage of the optical fiber body as a measurement sensor. The gratings are sections of the optical fiber with different refractive indexes, arranged in a grating pattern [9]. Light incident from one end travels through the fiber and as it reaches the grating, a certain wavelength (the Bragg wavelength) is reflected (Figure 1a). As the grating pitch is sensitive to strain and temperature, the Bragg wavelength component changes according to such factors. If a strain change of 1micro-strain occurs in the grating, the Bragg wavelength changes by 1.2 pm in the 1550 nm range.

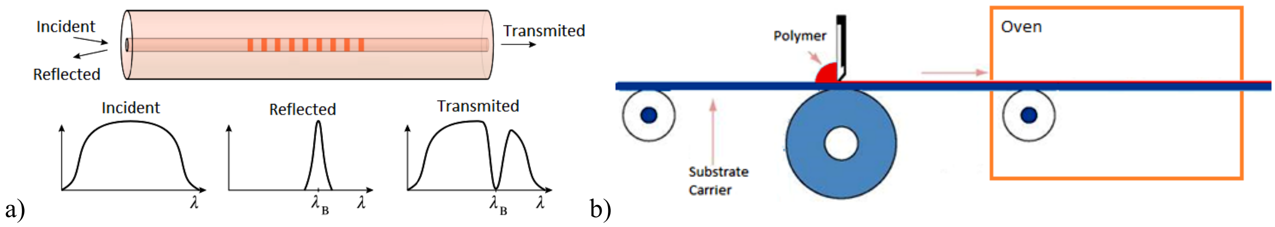


Figure 1 – a) FBG's working principle; b) Spread-Coating process illustration.

3. INTEGRATION APPROACH

In smart structure applications, the need for discrete (sometimes hidden) and integrated sensing solutions is much more relevant for areas where free space cannot be misused. Any kind of functional device should be integrated in the most discrete and elegant manner, in harmony with the surroundings. In the context of a flexible integrating approach for optical fiber sensor, a flexible skin-like foil is therefore the base material for the scope of this paper.

3.1 Foil Construction

The industrial manufacturing of flexible skin structure is mainly based on the spread-coating process. There are many variants of this relatively simple process. The designed process is adapted for the manufacturing of flexible laminates that can be composed of several layers and different materials.

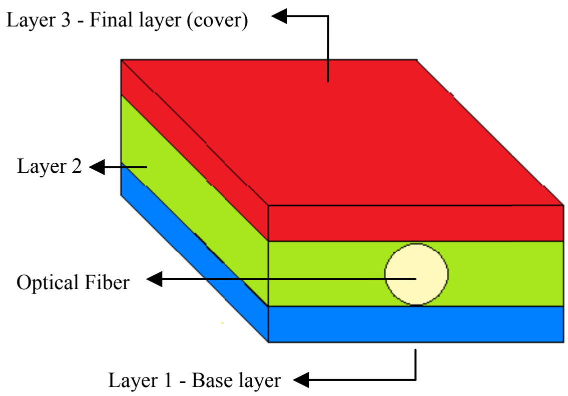
Figure 1b) illustrates schematically the process. The polymer is spread over the substrate carrier. The layer thickness of applied plastisol is controlled by precision setting the gap between the paper surface and the blade. Afterwards, it is driven through an oven, in which the geletion and fusion of the plastisol occurs, resulting in a solid but flexible structure. Finally, the substrate carrier is removed, releasing the flexible foil.

3.2 Foil Layout

Flexible skin foils can be made of different polymers. However, the low cost, manufacturability and structure performance, plasticized Polyvinyl chloride (PVC) was the best option. This certainly is one of the most versatile polymers, still playing a major role in the building, packaging and automotive, among other markets. Furthermore, PVC exhibits many advantages like highly competitive production cost, high resistance to ageing and ease of maintenance.

The integration of optical fibers and sensors in a PVC carrier may be done by bonding the optical elements on the carrier surface or by directly insertion in the carrier matrix. This last approach ensures low friction and low risk of damaging the optical elements. Furthermore, the insertion into the carrier matrix, guarantees a better and a direct bonding of optical fiber with the PVC matrix and subsequently a better stimuli transfer from the host material to the sensor.

In order to integrate the optical fiber in a PVC matrix by the spread-coating process, a sandwiched layout seemed to be the best approach (Figure 2a). The layer #1 plays the role of a protective skin for the optical fiber. This will be the visible layer after mounting the foil on the host structure. A thickness of 200 μm has been defined for this layer, and due to the flexibility of the process, this layer can be designed with different finishing styles. Although the optical fibers are flexible and can be easily bent, they tend to recover their initial shape. Consequently, it is necessary to bond the fiber to the substrate over which it is deposited, which is the goal of the middle layer. In order to accomplish the bonding, the PVC formulation of the intermediate layer has been specially designed. As the fiber had a 250 μm diameter, it was important to ensure the full wrap of the fiber. Thus, a 300 μm thick layer is the minimum required. Finally, a third PVC layer will serve as interface between the host structure and the smart structure. This layer formulation may also be customized concerning the adhesive that will be used to mount the structure. A thickness of 400 μm has been chosen for this final layer.



a)

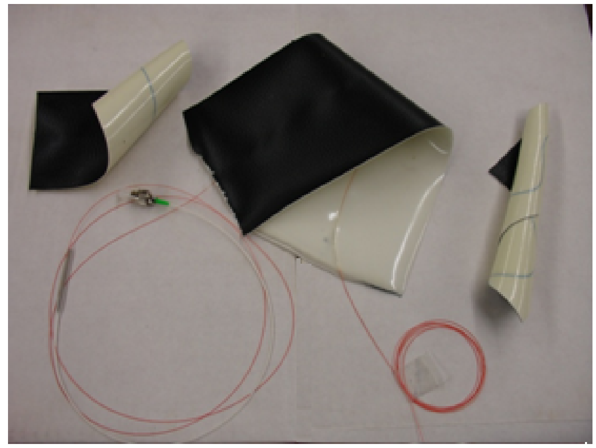
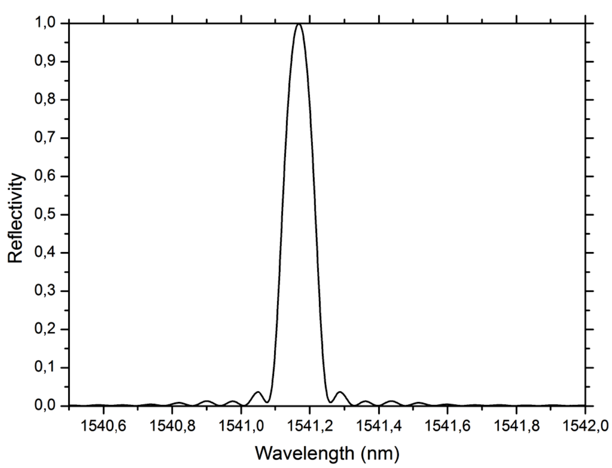

b)

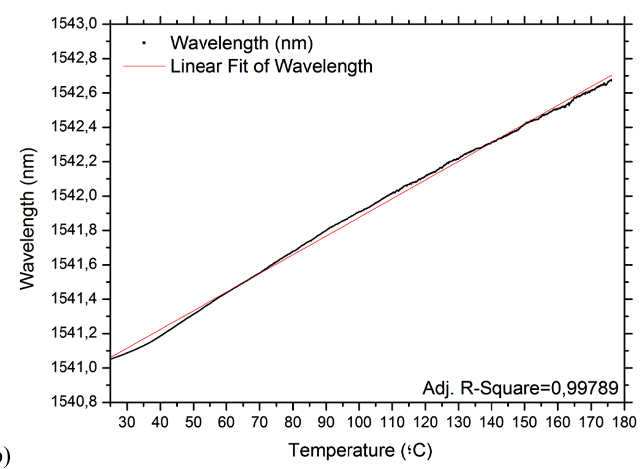
Figure 2 –a) structure for embedded optical elements in flexible PVC foil; b) Functional Prototypes.

4. RESULTS

Figure 2b) shows a successful prototype with a final thickness of 900 µm manufactured by spread-coating process. The fiber was well embedded in the polymer matrix, which ensured flexibility for the whole structure and protection regarding the optical fiber fragility. The FBGs utilized in these prototypes were produced by *FiberSensing* company[10]. The gratings were written in hydrogen loaded standard telecommunication fiber (SMF-28 type) using the phase mask technique and a pulsed *Excimer Laser*. The length of the gratings was 8 mm and the resonance wavelengths 1541.168 nm, corresponding to a refraction index modulation period of the core in the half-micrometer range. Before the characterization of the smart structure properties, the FBG signature has been read by a portable *BraggMETER FS4200* from *FiberSensing* and plotted in Figure 3a). From the spectrum it is possible to determine that there were no defects in the grating as its spectrum has the standard Bragg shape, meaning that the chosen approach for the embedding process did not represent any major concern. As a smart structure has its final application when mounted over a host in order to monitor it, a prototype was glued on a metal plate and then characterized regarding mechanical and thermal behavior. For the thermal evaluation, the metal plate was placed over a hotplate setup for cycles between 25-180 ºC. The Bragg response is plotted in Figure 3b). A fit was added according to the measured points and it was possible to establish a linear relationship between the sensor response and the temperature variation. Nevertheless, the Bragg pitch changed 0.01 nm/ºC.



a)



b)

Figure 3 – a) Reflected Spectrum; b) Temperature response of the smart structure.

The mechanical behavior of the structure was evaluated in a cantilever approach setup (Figure 4a). The metal plate was constrained at one end, while the other end was subject to 200 µm displacement cycles. The cycles were set at a 50 Hz frequency in a total of more than 4 million cycles. The FBG response has been monitor during the cycles and the initial response and final response are presented in Figure 4b). The FBG sensors have been able to follow with success the bending of the plate, resulting in a sinusoidal response, as it would be expected. In addition, with time, the response did not suffer any change regarding its characteristics. The initial sample and final sample share the same amplitude, shape and time response. Such behavior results from the successful bonding between the fiber and the PVC matrix, which was able to withstand the cycles without breaking the bonding.

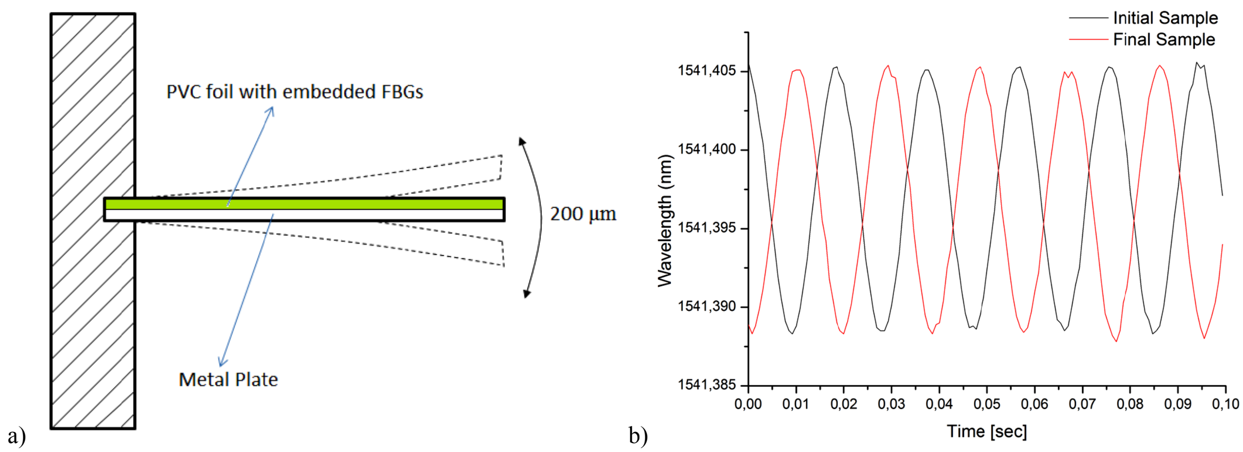


Figure 4 – a) Mechanical Analysis Setup; b) FBG response to strain cycles

5. CONCLUSIONS

There is a great interest in fiber grating sensors and in more recent years in the development of distributed strain and temperature sensor systems for application in smart structures systems. Nevertheless, it has been identified a lack regarding the automated methods for manufacturing smart-structures. The chosen process in this paper, takes advantage of flexible skin-foil structures manufacturing method by meeting its requirements and embedding fiber Bragg grating sensors. Functional prototypes have been produced without neglecting the sensor performance. Moreover, the sensing fiber integration was a success. The bonding between the fiber and the PVC matrix ensured the correct transference of mechanical and thermal stimulus. The integration of fiber optic FBG sensors was successfully achieved with a direct fiber deposition technique. The developed process was modified in order to be run in line during the normal manufacturing process for flexible laminated foils by spread-coating. The selected direct deposition of optical fibers during the spread-coating process for PVC foil manufacturing demonstrated to be practical for an industrial and automated production of flexible sensing foils.

ACKNOWLEDGMENT

Alexandre Ferreira da Silva is supported by Portuguese Foundation for Science and Technology (SFRH/BD/39459/2007). This work is also sponsored by FCT/MIT-Pt/EDAM-SI/0025/2008.

REFERENCES

[1] B. Lee, "Review of the present status of optical fiber sensors," Optical Fiber Technology, 9(2), 57-79 (2003).
[2] K. T. V. Grattan, and T. Sun, "Fiber Optic Sensor Technology: an overview," Sensors and Actuators A: Physical, 82, 40-61 (2000).
[3] A. D. Kersey, M. A. Davis, H. J. Patrick *et al.*, "Fiber grating sensors," Lightwave Technology, Journal of, 15(8), 1442-1463 (1997).
[4] E. J. Friebele, C. G. Askins, A. B. Bosse *et al.*, "Optical fiber sensors for spacecraft applications," Smart Materials and Structures, 8(6), 813 (1999).
[5] N. Schiller, "Selecting Optical Detectors for Automotive Designs," ECN: Electronic Component News, 1 (2004).
[6] [Sensing Issues in Civil Structural Health Monitoring] Springer, (2005).
[7] G. T. Kanellos, G. Papaioannou, D. Tsiokos *et al.*, "Two dimensional polymer-embedded quasi-distributed FBG pressure sensor for biomedical applications," Opt. Express, 18(1), 179-186 (2010).
[8] M. Nishiyama, and K. Watanabe, "Wearable Sensing Glove With Embedded Hetero-Core Fiber-Optic Nerves for Unconstrained Hand Motion Capture," Instrumentation and Measurement, IEEE Transactions on, 58(12), 3995-4000 (2009).
[9] R. Kashyap, [Fiber Bragg Gratings] Elsevier, (2010).
[10] FiberSensing, [www.fibersensing.com].