Manufacturing Technology for Flexible Optical Sensing Foils

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Abstract - **This paper presents the development of an integration technology that offers a breakthrough solution for the industrial manufacturing of flexible smart materials with optical sensing features. Subsequently, it aims the development of a flexible substrate, or foil, in which optical waveguides and sensing elements are integrated in line during the manufacturing process of the substrate itself. This artificial and flexible optical sensing foil can then be applied to regular or irregular surfaces, enabling a quasi-distributed strain map. Fabrication, using industrial processes, and characterization of a polymeric foil able to sense, gather and send sensitive information for remote analysis is explored. The propose smart material uses Fiber Bragg Grating sensors embedded in standard laminated polymeric sheets used in different industries, as automotive or aeronautic. The definition of the whole integration process as well as the PVC paste custom formulation for better integration results is described. The presented optical sensor incorporated in the polymeric foil is fully functional with high sensitivity, 0.6 pm/μstrain, measuring deformation, up to 1.2 mm.**

I. INTRODUCTION

Optical sensing technologies have associated advantages that make them very attractive in a broad range of applications. Optical fiber sensors, in particular, provide low cost solutions, with immunity to electromagnetic interference, multiplexing capabilities and a high degree of miniaturization and integration. Presently, optical fiber sensors offer a high performance alternative, in comparison to standard technologies, in many different areas, either for measuring physical parameters like strain, temperature or pressure, or for performing highly sensitive biochemical analysis [1, 2].

Optical sensors have evolved considerably from their beginning as experimental devices. Better instruments and sensor packages have helped make installation a bit easier [3]. Nevertheless, about 50 % of the cost of such systems is for installation. This is mainly due to the use of manual or semi-manual deposition or integration techniques of optical fibers and sensors [3]. In this context, automated ways for integration of sensors in sensing structures is the crucial point. Furthermore, the concept of the optical sensors itself has to be developed in such a way that the sensor element or module can be manufactured in line, or at the same time, as the monitoring structure. This would significantly simplify the installation of sensor modules in those structures.

The link between textiles or polymer-laminates with optical devices and electronics is more realistic than ever. An emerging new field of research that combines the strengths and capabilities of electronics, optics and textiles is opening new opportunities. Low-production cost, wide exploitation of integrated circuit technology and wide applicability to sensor arrays ensure the integration of microsensors in almost any structure, providing the desired system data.

II. FIBER BRAGG GRATING SENSOR

Fiber Bragg Gratings (FBG) consist in a periodic modulation of the refraction index along the fiber. The gratings produced are typically around 10 mm long. When an optical beam is injected into the fiber containing the grating, the wavelength spectrum corresponding to the grating pitch will be reflected, while the remaining wavelengths will pass through the grating undisturbed, as exemplified in Figure 1[4].
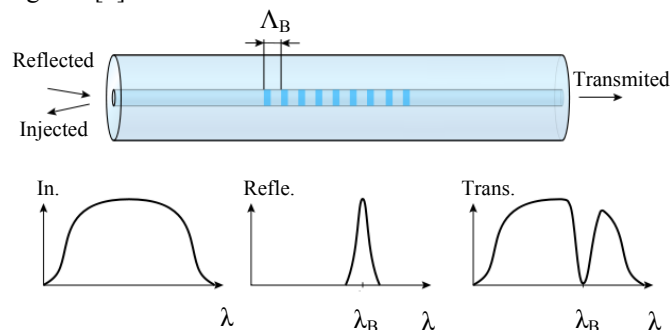

Fig. 1 – Illustration of a Bragg sensor principle.

Since the grating period structure is sensitive to strain and temperature, these two parameters are measured by the analysis of the reflected light spectrum.

The resonance wavelength is named as Bragg wavelength, λ_B, and the dependency in the period of the diffraction Bragg network, Λ_B, is obtained by:

$$\lambda_B = 2n_{eff} . \Lambda_B, \qquad (1)$$

where n_{eff} is the effective refraction index of the fiber. When depending on the effective refraction index associated to the fiber (core and cladding refraction indexes) and on the diffraction network period, the Bragg wavelength will depend on the physic quantities that may change these parameters, while interacting with the fiber. Like the majority of the optical sensors, the Bragg sensors are intrinsically sensitive to

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temperature, axial and transversal deformation, and pressure. But, through these sensibilities and especially by the axial deformation, the Bragg sensors can be used for other physical measurements. Equation (1) implies that the reflected wavelength λ_B is affected by any variation in the physical or mechanical properties of the grating region. For example, strain on the fiber changes Λ_B and n_{eff}, via the stress-optical effect. Similarly, changes in temperature lead to changes in n_{eff} via the thermo-optical effect and, in an unconstrained fiber, Λ_B is influenced by thermal expansion or contraction. This situation is expressed in equation 2, where the first term on the equation gives the effect of strain on λ_B and the second describes the effect of temperature.

$$\Delta\lambda_B = \lambda_B\,(1-\rho_\alpha)\,\Delta\varepsilon + \lambda_B\,(\alpha+\xi)\Delta T, \qquad (2)$$

where $\Delta\lambda_B$ is the change in Bragg wavelength, ρ_α, α and ξ are respectively the photoelastic, thermal expansion and thermo-optic coefficients of the fiber, $\Delta\varepsilon$ is the change of strain and ΔT is the temperature change [5].

Unlike traditional resistance strain gages, FBG sensors are completely passive, offering inherent insensitivity to environmental induced drift and the possibility to obtain, simultaneously, temperature information. The main advantage to use Bragg gratings is their multiplexing potential [4]. Many gratings can be written in the same fiber at different locations and wavelengths tunes. This allows the strain mapping along a single fiber. However, since the gratings have to share the spectrum of the light, there is a trade-off between the number of gratings and the dynamic range of the measurements on each FBG.

III. POLYMERIC FOIL

Flexible skin-like foils can be made from many different polymers. Polyurethane (PUR) can be one of them with very long durability, high performance in regard to abrasion resistance and flexibility. However, PUR-based foils are one of the most expensive materials in the field of flexible polymeric foils. Polyolefin based artificial skins are a suitable alternative for the required objective, but their flexibility and performance related to softness, abrasion and flexibility is in general more difficult to adjust.

As the research is focused on the development of a generic manufacturing technology for a flexible optical sensing foil, a polymer matrix with an acceptable average quality and price is desired. The choice was set on plasticized Polyvinyl Chloride (PVC), for its general good cost/performance ratio and friendly use during manufacturing processes. Another interesting aspect of PVC is that it can be used with different processing techniques compared to all other polymers.

IV. SMART STRUCTURE FABRICATION

The damaging of the integrated optical sensing elements must be avoided. The integration of optical fibers and sensors in a PVC carrier may be done by: (1) bonding the optical elements on the carrier surface - higher friction and risk of damaging of optical elements; (2) optical elements insertion in the carrier matrix – low friction and low risk of damaging the optical elements. The second possibility is more advisable

in respect to the protection given to the optical elements. Furthermore, the insertion into the carrier matrix, guarantees a better bonding of optical fiber with the PVC matrix and subsequently a better transfer of stimuli from the host material to the sensor. For this purpose, a multilayer structure approach is the most suitable (Figure 2).

PVC-layer 3: Final layer (cover)

PVC-layer 2 with embedded Optical Fiber

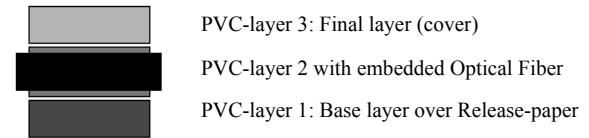PVC-layer 1: Base layer over Release-paper

Fig. 2 – Multilayer structure for embedded optical elements in flexible PVC foil.

The layer #1 plays the role of a protective skin for the optical fiber. Optical fibers are flexible and can be easily bent but they tend to recover their initial shape. Therefore, it is mandatory to bond the fiber to the substrate over which it is deposited. The use of adhesives polymers can be avoided by an intermediate PVC layer. This layer plays the role of an adhesive layer for optical fiber. The density and, especially, the whole formulation of this layer are responsible for the fiber adhesion to the carrier and keep it steady in its place. Finally a third PVC layer is applied as cover layer.

With the structure layout defined, the fabrication process starts by the fabrication of the FBG sensors and subsequent the integration stage by an industrial process.

A. Optical Fiber Sensor Fabrication

Figure 3 illustrates the experimental setup used for fabrication of Bragg structures by the phase mask method.
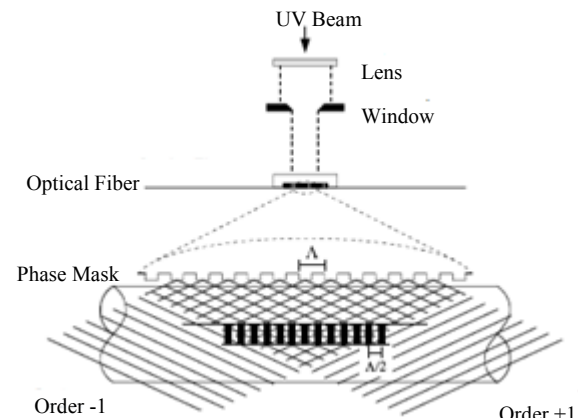

Figure 3 – Schematic of the FBG fabrication setup.

The optical fiber is maintained along the surface of the mask aligned transversely with the depressions, and the UV radiation focused along the optical fiber through a cylindrical lens. Each individual component of the FBG microstructure is formed by irradiation spot of the fiber core, which locally causes a change of the refraction index on adjacent positions not exposed. It should be noted that, in an ideal mask, the period of the modulated interference pattern is always half of the period of the phase mask, and independent of wavelength of the laser emission (Figure 3). The period of the modulated interference pattern depends only on the period of the phase

mask. The manufacturing of the Bragg structure with different wavelengths requires the use of different phase masks. The extreme simplicity of alignment and stability of the inherent pattern of interference can produce networks of Bragg with high reproducibility.

The FBG sensors were inscribed at the communication wavelength range (1520-1570 nm) in a single mode *Corning 28e*, a standard optical fiber for communication applications.

B. Polymeric Foil Fabrication (Integration)

The fabrication of the structure described in Figure 2 is based on the application of multiple PVC layers. For this type of multi-layer structure, the best industrial process is the spread coating (Figure 4). It consists on the deposition of one or more layers of plastisols on a support such as paper, that are cure afterwards in an oven. Because of its versatility, this technique constitutes an optimum choice for the development of flexible optical sensing foils.
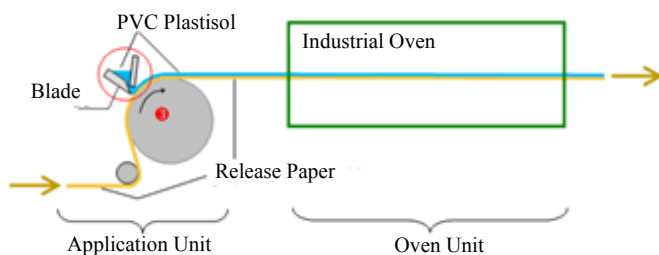

Fig. 4 – Layout of industrial spread-coating process.

A *Werner Mathis®* coating equipment was used for the production of laboratory scaled flexible PVC foils with embedded optical fibers. A first layer was applied on a structure that works as support during the process. After the thickness homogenization, the layer is cured in the oven. The second layer is deposited over the first layer. This layer was specially formulated to improve the fiber adhesion. After the thickness homogenization, the fiber was placed in the second layer and then putted in the oven. The final layer was placed over the previous layer and fully cured in the oven.

V. RESULTS AND DISCUSSION

Figure 5 shows the functional prototypes produced as previously described. The polymeric foil, cropped to 50x100 mm^2 size, had a Bragg sensor embedded in it. By visual inspection, no damage was detected, a good indicator of the fabrication processing steps success. By touch, the fiber was not felt, sustaining the idea of a good integration level.

Visual examinations of polymeric layer #1 showed that once the skin layer is cured, the optical fibers deposited on its surface did not penetrate in its core. It was possible to reduce the thickness of this layer to 150 μm. With a thicker skin layer, the whole construction became less flexible, heavy and would contribute for a sensitive loss in the fiber. The thickness of layer #2 started at 300 μm, which proved to be satisfactory, but it was reduced to 250 μm. Low thickness was feasible from the integration point of view, but the

deposited fiber unsteadiness became more visible. Therefore, a thickness of 250 μm is more appropriate. The thickness of 150 μm for the layer #3 was chosen considering a minimum thickness necessary for the mid-layer protection.
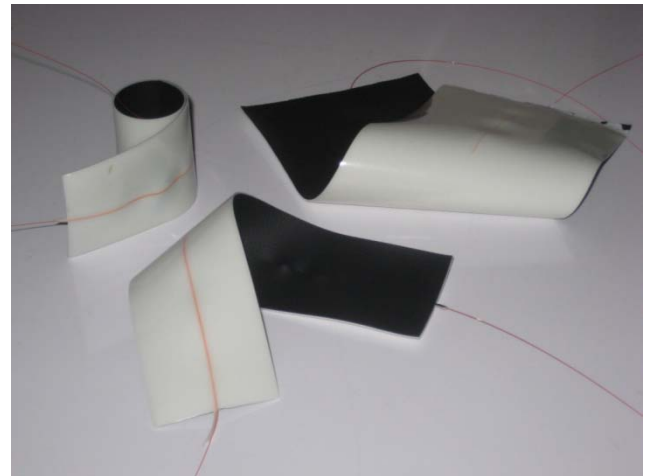

Fig. 5 – Fabricated prototypes.

Since the sensors integration in an industrial environment is desired, the process constraints had to be evaluated. In this case, temperature value and exposed time were analyzed. Several foils with integrated optical fibers were fabricated at different temperatures, from 200 to 240 ºC with 20 ºC steps, and at different cure time durations, from 60 to 180 seconds with 30 seconds steps. The PVC from the polymeric foil did not stand temperatures above 240 ºC during 150 seconds. At the sensor level, all the FBGs withstood the temperature and the cure duration, without sensitivity loss or damage. As the foils are fabricated at 220 ºC for 60 seconds, these results do not present any limitations. Finally, the integration procedure that best fit our goal is presented in Table 1.

Table 1 – Standard fabrication procedure.

Step	Operation	Condition		
		Gap [μm]	Temp. [ºC]	Heating time [s]
1	Application of PVC-layer 1	150	-	-
2	Heat-curing of PVC-layer 1	-	220	60
3	Application of PVC-layer 2	250	-	-
4	Optical fibres insertion	-	-	-
5	Heat-curing of PVC-layer 2	-	220	60
6	Application of PVC-layer 3	150	-	-
7	Heat-curing of PVC-layer 3	-	220	60
8	Cooling + manual release	-	-	-

The prototypes were tested over an *Instron® 4302* testing machine at the same time that the optical signal was being measured by a *BraggMETER™* unit from *FiberSensing* [6].

The model was subjected to a displacement at the rate of 16 μm/s. As it is demonstrated over the graph (Figure 6) the wavelength deviation had a linear behavior from 0.5 % ahead. Under 0.5 %, the low resolution of the testing machine for this elongation range can be pointed to justify the nonlinear behavior. Besides this fact, the model was able to be stretch

1.2 % (1.2 mm), when subject to a load of 9.691 N. With the 1.2 mm displacement related to the 5.877 nm wavelength deviation, a sensitivity of 0.6 pm/µε (picometer per microstrain) can be determined. This value provides a qualitative measurement about the integration quality.

Also, the displacement was applied in steps of 0.2 % (200 µm) to verify if the fiber slipped inside the foil (Figure 7). If that happened, the optical signal should decrease while keeping the displacement constant. After each step, there was a little bump, but in seconds the optical signal became constant. The small variation may be due to the vibration of the testing machine claw, as the model presents high sensitivity.
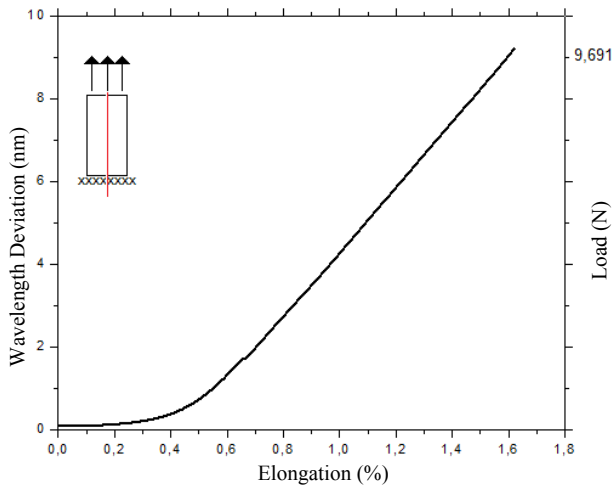

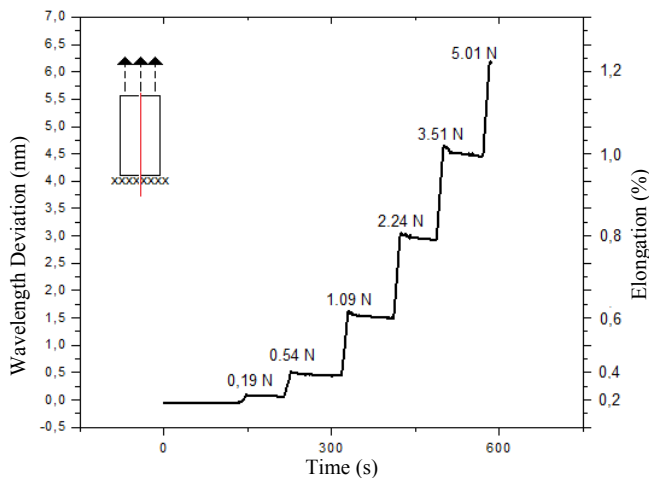Fig. 6 – FBG response to applied displacements.

Fig. 7 – FBG response to applied displacement steps (200 µm).

VI.   APPLICATIONS

The range of applications of this type of smart structures with integrated sensors is wide. For instance it can provide information (localization of defects, acquisition of strain and temperature maps during processing, etc) that would be interesting for automotive applications and insurance companies. The number and sophistication of optoelectronic systems found in modern vehicles is increasing at an unprecedented level [7]. Presently, electronics and photonics account for nearly 25 % of total vehicle manufacturing costs [8]. In this context, the development of advanced optoelectronic systems with integrated sensing and data transport capabilities is a key step for the implementation of a new generation of smart structures. The main technological innovation would be the development of an inner transportation smart flooring at low-cost, using emerging technologies, advanced materials process and manufacturing for monitoring the main frame structure deformation in case of collision, accident or to be used during the development of the vehicle.

VII.   CONCLUSION

The full integration of FBG sensor in a polymeric foil, using standard industrial fabrication processes was described. The integration of FBG sensors into the polymeric foil was evaluated in terms of the fabrication process, cure temperature, integration level (adhesion of the fiber to the polymeric foil) and sensor sensitivity. The result was the definition of the whole integration process as well as the PVC paste custom formulation for better integration results. The structure is characterized by an interesting performance, namely, a sensitivity of 0.6 pm/µstrain, a linear behavior, maintenance of the spectrum shape during the force application and also showed good repeatability. It also returned to its initial position when the structure was released from the efforts and there was no reduction of the signal amplitude. Integration of FBG based-sensors in PVC foils was demonstrated, promising the possibility of mass production in industrial environment. With the achievement of this structure, it is possible to provide a sensing solution that best fits the host structure monitoring requirements. Also, integration of optical sensors, like Fiber Bragg Gratings, in textiles would be a promising solution in the future.

VIII.   ACKNOWLEDGMENT

IX.   REFERENCES

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