PVC Smart Sensing Foil for Advanced Strain Measurements

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***Abstract*—Monitoring systems can already be found in common applications, from automotive to aeronautics or biomedical. However, the application of these monitoring systems has not yet been a very easy task, especially, at the sensor application step. A smart structure with sensing capabilities would allow to overcome the existing issues in the installation of sensor networks. As the size of this type of systems and the market requirements are significant, an industrial manufacturing process needed to be considered. An integrated solution based in Fiber Bragg Grating sensors embedded in PVC laminates was manufactured by industrial spread-coating process. The resultant structure is a temperature and strain sensitive foil that was characterized in terms of surface structure, optical response and overall performance. The integrated solution behavior had a slope of 0.8 pm by microstrain with a measurement range of 1.2 mm when the fiber was straight in the foil. Different fiber layouts were also tested and defined the minimum curve radius in 10 mm. The foil also presented a dimensional stability above 99%, ensuring the capability to sustain molding process. A mechanical analysis to evaluate the elongation capabilities and optical response was conducted. Three samples with different sensor positioning were subjected to the test. In the end, a sample, with the sensor in a 45° angle regarding the displacement axis, achieved the best compromise between maximum elongation range (25%) and optical response linearity. For the temperature response, a wavelength deviation of 1.7 nm was obtained for a 100 °C temperature change.**

***Index Terms*—Fiber Bragg gratings, fiber-optic sensor, integrated sensor, sensor for structural monitoring.**

I. Introduction

OPTICAL sensing technologies have associated advantages that make them very attractive in a broad range of applications, from biomedical [1] to civil engineering [2], aeronautics [3], or automotive applications [4]. Optical fiber sensors, in particular, provide low cost solutions, with immunity to electromagnetic interference, multiplexing capabilities, and a high degree of miniaturization/integration. Presently, optical fiber sensors offer a high performance alternative, in comparison to standard technologies, either for measuring physical parameters like strain, temperature or pressure, or for performing highly sensitive biochemical analysis [5], [6].

Although the optical fiber sensors present a higher performance when compared to the standard sensing technologies, its application *in situ* has been one of the major existing issues. In the majority of the cases, the fiber optic sensors are attached to the surface, using epoxy resins [7], woven fabrics [8] or even by welding methods [9]. These approaches present a few concerns due to the fragility of the optical fiber and in optical signal issues as macro- and micro-bendings. These concerns are one of the main barriers for choosing this type of technology. The solution for overcoming these issues have been already proposed in different works by the integration of sensing devices in substrates that are then connected to the host structure [10]–[12]. They were all produced in a laboratory environment, requiring, at this stage, an industrial scale-up for achieving a ready-to-market solution [10]–[12].

The proposed smart structure was designed to be fabricated by already existent industrial processes. Nevertheless, the incorporation of optical sensors creates a few difficulties in eventual sensor maintenance or replacement. Thus, it is proposed the incorporation of optoelectronic instrumentation in standard polymeric foils that can be already found in different products, e.g., automotive and aircraft interior trimmings, wall coverings or in sports suits. The advantages of such smart structure come from the easy applicability of the foils modules in the monitored structure, as well as, easy access for replacement.

Moreover, integrated optical devices are now emerging as the next generation of sensing structures, where virtually any parameter can be determined with high accuracy in a highly miniaturized optoelectronic device [13]. The link of polymer laminates with optical devices and electronics is becoming realistic, enabling its application in any type of surface level.

II. PVC Foil With FBG Sensor

The smart structure based on the integration of strain sensors in polymeric foils is mainly constrained by the fabrication techniques in industrial environment. The majority of the common polymeric foils with customization possibility are based on the spread-coating process.

A. Integration Technology

Spread-coating technique consists on the deposition of one or more layers of plastisols on a support, such as paper, that is

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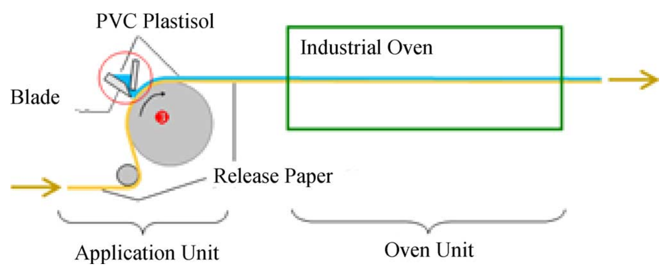

Fig. 1. Layout of industrial spread-coating process.

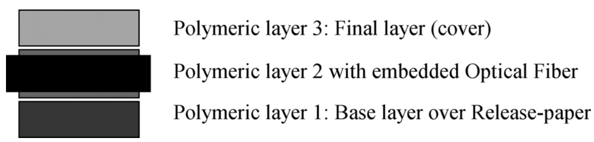

Fig. 2. Multilayer structure for embedded optical elements in flexible PVC foil.

cured afterwards in ovens (Fig. 1). Because of its versatility, this technique constitutes an optimal choice for the development of flexible optical sensing foils.

When developing a flexible sensing structure, the need for an easy to apply product becomes evident. In this context, the sensing product should be handled, avoiding damaging the integrated optical sensing elements.

On the other hand, it is important to ensure a good bonding between the sensor and the foil substrate to ensure the minimum sensitivity loss by the polymeric component. Also, the thickness of the whole structure should be the minimum possible, or at least, the distance between the integrated sensor and the host structure should be minimized. This ensures that the existent polymeric layer between the host structure and sensor is reduced, guarantying the transference of the structure behavior stimulus with the minimum interference.

Another requirement for the structure is its ability to be applied in regular and irregular surfaces, enabling a broader application field. This feature requires flexibility and dimensional stability from the sensing structure to sustain some application methods as thermo or vacuum forming.

Consequently, optical fibers and sensors integration should be done by inserting them directly in the carrier matrix and not bonding the optical elements on the carrier surface. With the sensors inside the polymeric matrix is possible to ensure low friction and low damage risk. Furthermore, it guarantees a better bonding of optical fiber with the polymeric matrix, and subsequently a better transfer of stimuli from the host material to the sensor. For this purpose, a multilayer structure approach was chosen (Fig. 2).

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 adhesive polymers is avoided by an intermediate layer (layer #2). The density and, especially, the whole formulation of this layer are responsible for the fiber adhesion to the carrier and for keeping it steady in its place. Finally a third layer is applied as cover layer.

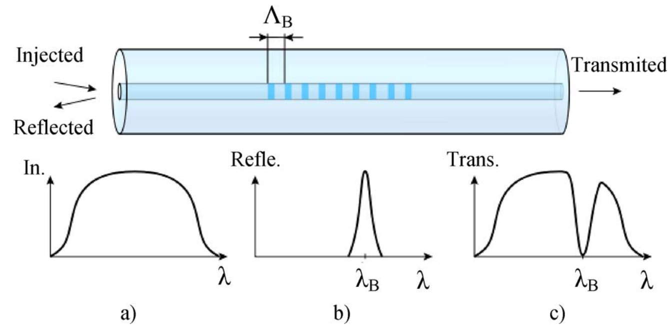

Fig. 3. Illustration of a Bragg sensor working principle: (a) incident spectrum, (b) reflected spectrum, and (c) transmitted spectrum.

B. Optical Fiber Bragg Gratings (FBGs)

Fiber Bragg Gratings (FBGs) consists in a periodic modulation of the refraction index along the fiber. The produced gratings are typically around 7 mm long. When an optical beam [Fig. 3(a)] is injected into the fiber with the grating, the wavelength spectrum corresponding to the grating pitch will be reflected [Fig. 3(b)]. The remaining wavelengths will pass through the grating undisturbed, as illustrated in Fig. 3(c) [14].

Since the reflected wavelength depends on the refraction index associated to the fiber 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. Consequently, the Bragg sensors are intrinsically sensitive to temperature, axial and transversal deformation, and pressure. Through these sensibilities and especially by the axial deformation, the Bragg sensors can be used for other physical measurements.

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 its multiplexing potential [14]. Many gratings can be written in the same fiber at different locations and wavelengths tunes. This allows the creation of a strain map along a single fiber. However, since the gratings have to share the spectrum of the light along the fiber, there is a tradeoff between the number of gratings and the dynamic range of the measurements on each FBG.

C. Polymeric Foil Material

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. Flexible skin-like foils can be made from many different polymers [15].

Polyurethane (PUR) can be one of them with very long durability, high performance in regard to abrasion resistance and flexibility [15]. 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 its softness range and performance, abrasion and flexibility is in general more difficult to adjust [15].

The choice was set on plasticized polyvinyl chloride (PVC), for its general good cost/performance ratio and friendly use during manufacturing processes. The PVC is a highly viscous

TABLE I
FABRICATION PROCEDURE

Step	Operation	Condition		
		Gap [μm]	Temp. [°C]	Heating time [s]
1	Application of PVC-layer 1	200	-	-
2	Heat-curing of PVC-layer 1	-	200	60
3	Application of PVC-layer 2	300	-	-
4	Optical fibers insertion	-	-	-
5	Heat-curing of PVC-layer 2	-	200	60
6	Application of PVC-layer 3	400	-	-
7	Heat-curing of PVC-layer 3	-	200	60
8	Cooling + manual release	-	-	-

mixture that becomes solid on heating. When cooled, the plastisol provides a tough material with good physical characteristics and with a service temperature range of 0 °C to 125 °C [16]. Long-term flexibility is the main advantage, which means that the plastisol supports relative motion between host substrates [16]. The major drawback is the cure temperatures that may be too high, limiting their use on specific substrates or applications.

III. SMART STRUCTURE FABRICATION

Werner Mathis® coating equipment was used for the production of laboratory scaled flexible PVC foils with embedded optical fibers. This laboratory technique enables industrial process conditions simulation and is perfectly suitable for industrial scale up.

Since the polymeric layer #1 is cured, the optical fibers do not penetrate in its core. The layer thickness was approximately 200 μm. With a thicker skin layer, the whole structure became less flexible, heavy and would contribute for a sensor sensitivity loss. Layer #2 thickness was defined to 300 μm, taking into account the 250 μm fiber outer diameter. Lower layer thickness would be also feasible from the integration point of view, but the deposited fiber unsteadiness would become more visible. For the final layer, a 400 μm thick layer was chosen to ensure enough protection to the optical fiber.

The integration of the optical sensors requires the use of process parameters well-defined during the fabrication. For this specific case, exposing temperature and duration were the main parameters to take into account. The polymer was only able to sustain a maximum of 240 °C for 150 s, while the fiber could go beyond this value. Thus, the polymer characteristics were the features that constrained the integration process. Most polymeric foils are fabricated in a temperature range of 200 °C–220 °C for 60 s, which is perfectly feasible for this specific case.

The integration procedure that best fit our goal, considering the grounds mentioned above, is presented in Table I.

The fiber Bragg gratings, utilized in these experiments, were produced by FiberSensing. The gratings were written in hydrogen loaded standard telecommunication fiber (Corning SMF 28e+) using the phase mask technique and a pulsed Excimer Laser. The length of the gratings is 8 mm and the resonance wavelength is 1541 nm, corresponding to a refraction index modulation period of the core in the half-micrometer range (≈ 0.52 μm), based on the effective refractive index of 1.47.

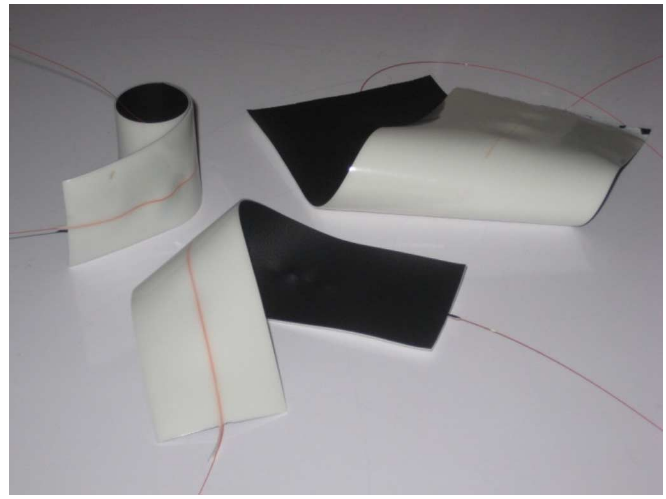

Fig. 4. Fabricated prototypes.

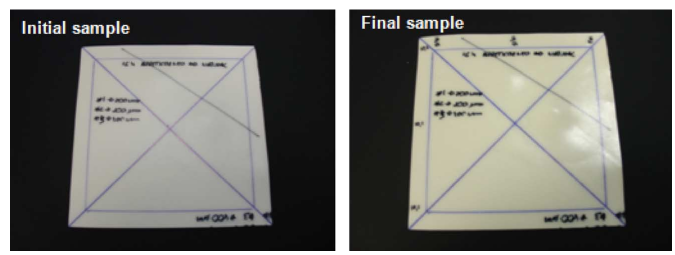

Fig. 5. Dimensional stability test samples, before and after the test.

IV. RESULTS AND STRUCTURE CHARACTERIZATION

Fig. 4 shows fully functional prototypes produced by spread-coating process as previously described.

A. Surface Characterization

By visual inspection, no damage was detected, which is a good indicator of the fabrication processing steps success. By touch, the fiber was not felt, sustaining the idea of a good integration level.

The samples were analyzed at the dimensional stability level. The performed tests evaluated the ability of the structures to retain their shape when submitted to high temperature during a period of time. The initial dimensions were taken at reference marks. Then, the structures were placed in an oven at a specific temperature and exposure time, and, afterwards, reconditioned to room temperature for 1 h. After cooling down, the dimensions were measured again at the same reference marks and compared to the initial values. Two tests conditions were considered, where the samples were first in the oven for 60 min at 80 °C and then 1 min to 190 °C.

In both runs, the samples did not present any significant dimension changes. The variations did not reach 1%, which is a very small value and acceptable, in the industry, for PVC foils (Fig. 5).

These results ensured that this PVC matrix provides a secure structure for the molding stage. It was stable enough to be applied in regular and irregular surfaces without presenting major concerning at the formulation level.

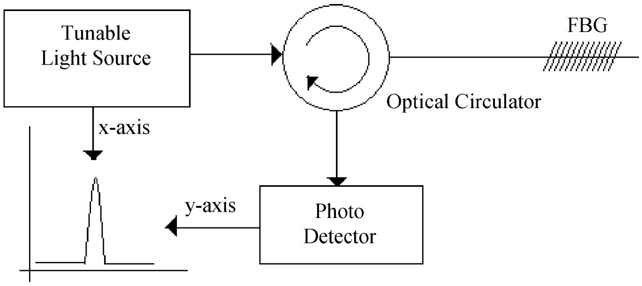

Fig. 6. Interrogation unit setup schematic.

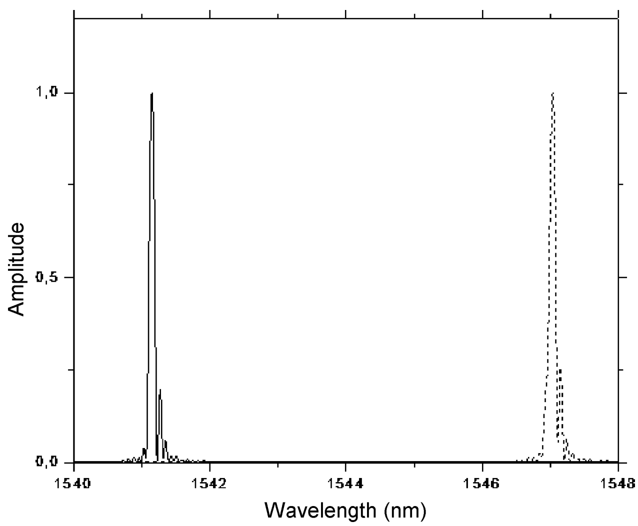

Fig. 7. Reflected spectrum from the FBG sensor for two distinct tensile forces.

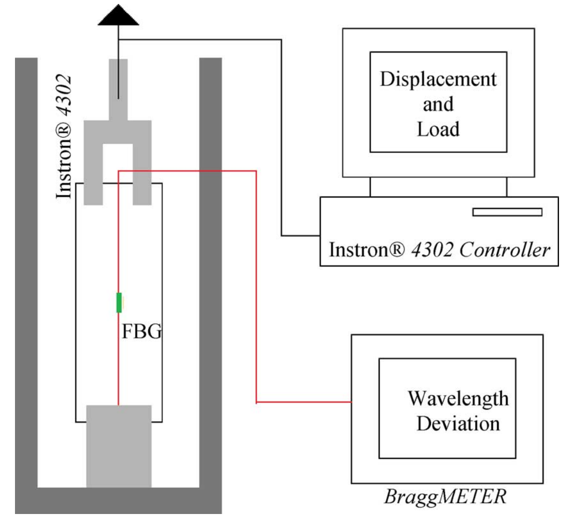

Fig. 8. Testing setup for sensitivity.

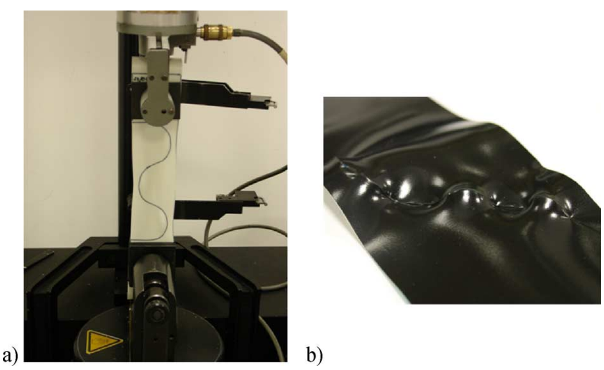

Fig. 9. (a) Sample gripping in elongation-at-break test and (b) detail of the sample surface after the elongation.

Also, the fine-tuning of the PVC matrix properties can be redirected to specific end-uses of the sensing foil. The selected assembly itself can be adapted to special needs. More layers can eventually be added if there is a need for stronger protection of the fibers or a damping effect for the transmitted external stimuli to the optical fibers. Furthermore, one or more layers made of different materials than PVC can be added to the structure. All those changes can be applied to develop a flexible sensing concept according to the needs for the final application.

B. Optical Sensor Characterization

The optical signature of the Bragg sensor was first acquired by an interrogation unit BraggMETER™ 4200 unit from FiberSensing. This interrogation unit sweeps the 1520–1570 nm wavelength range and retrieves information about the optical signal amplitude (Fig. 6).

Fig. 7 presents the reflected spectrum of the FBG sensor. The side lobes came from the grating fabrication process, resulting from the radiation transmission function, and not from the integration process. The lobes can be later smoothed by apodization. When stretching the polymeric foil, the embedded FBG sensor followed the deformation and the reflected spectrum suffers a wavelength deviation. When the sample is released, the spectrum returns to its initial position.

C. Structure Characterization

Until this stage, data about the individual components of the structure have already been evaluated. In terms of the PVC matrix, the results showed a stable structure, with dimensional stability. The optical sensors were able to sustain the fabrication process without any damage. The optical signal was measured with success.

Also, it is important to evaluate the performance of the overall structure, in order to infer about its sensitivity and integration level. For such goals, the prototype was tested over a setup (Fig. 8) composed by a Instron® 4302 testing machine, while the optical signal was being measured by the BraggMETER™ 4200 unit.

The mechanical study of deformable PVC sensing foils was based on tensile tests [Fig. 9(a)]. The resistive behavior to mechanical stretching of the flexible sensing foils is altered due to the presence of optical fibers. This behavior is dependent of the configuration of the optical fibers or on the optical fiber path in the PVC matrix. These dependencies were better evaluated by the several prototypes that were produced, with different paths of the inserted optical fibers.

When stretching all the considered samples, it was possible to detect a good integration level. In all the samples, the fiber was kept inside the polymeric foil, sustaining the PVC wrinkles due to the stretching in a few specific samples [Fig. 9(b)].

The first set of prototype samples were cut to a 50 $\times$ 100 mm size strap and two tests were performed.

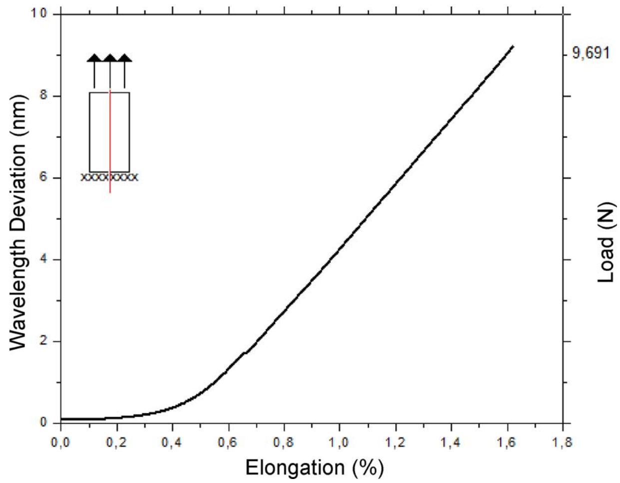

Fig. 10. Wavelength response to applied displacements.

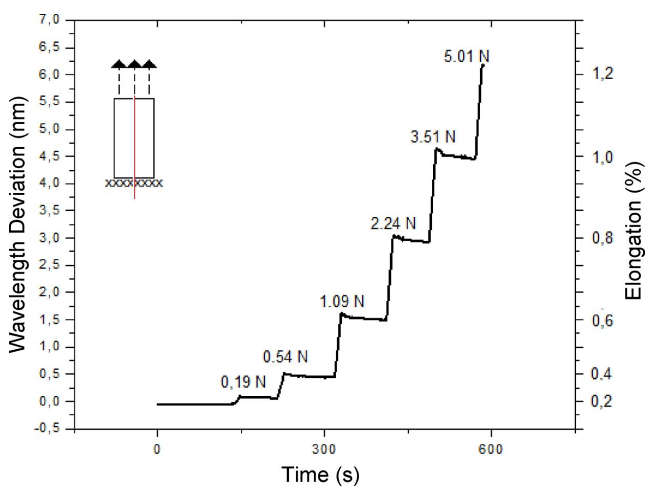

Fig. 11. Wavelength response to applied displacement steps.

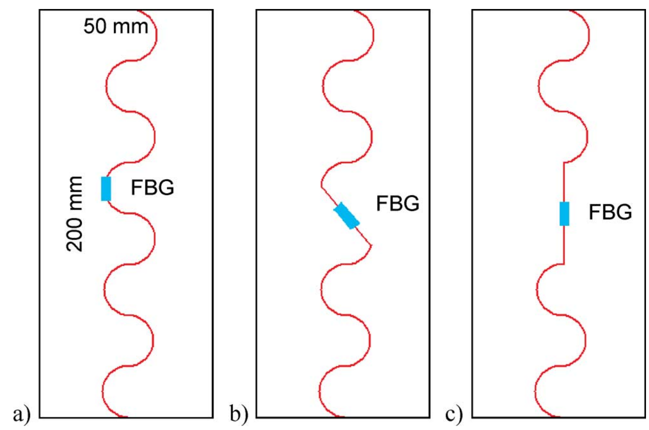

Fig. 12. Illustration of the samples layout considered for the mechanical characterization: (a) Bragg sensor in the curve; (b) Bragg sensor in straight line at 45° angle; and (c) Bragg sensor in straight line at 90° angle.

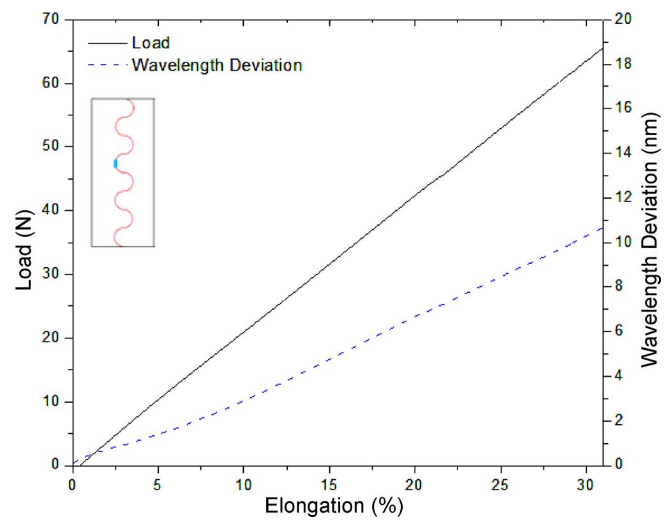

Fig. 13. Sensor response with the Bragg structure in a curve shape.

In the first test, a displacement was applied at a constant increment rate of 16 μm/s. As it is demonstrated over the graph (Fig. 10), the wavelength deviation had a linear behavior above the 0.5% elongation state. Under 0.5%, the nonlinearity was mainly due to initial stretch state of the sample. At the initial instant, the distance between the grips of the testing machine was lower than the effective length of the foil between the grips due to the foil flexibility.

Besides this fact, the model was able to sustain the 1.62% stretching, which is 1.62 mm of displacement in this case. At this time, the fiber was subject to a load of 9.691 N. This displacement of 1.62% is followed by a wavelength deviation of 9.207 nm, defining the present model response to 0.8 $\mathrm{pm}/\mu\varepsilon$ (picometer per microstrain). If this structure was applied to a one meter long steel beam that had been stretched one millimeter, the wavelength deviation that would be measured is 0.8 nm. The determined response value provides a qualitative measurement about the integration quality.

Finally, a displacement was applied in steps of 0.2% (200 μm) and kept at that state during a period of time, in order to evaluate if the fiber slipped over the polymeric foil (Fig. 11). If that happened, the optical signal should decrease while keeping the displacement constant. In Fig. 11, it can be seen a little bump after each step, but in seconds the optical signal stayed constant. When stopping the displacement, vibration of the claw was observed and detected by the FBG sensor due to its high sensitivity. The preservation of a constant value ensures that the fiber did not slip and that it was well embedded in the foil.

In the second set of samples, the fiber was mainly set in an "S" pattern with a curve radius of 10 mm. This radius value was considered the minimum that can be successfully done. Lower radiuses (< 10 mm) are not so easy to accomplish during the fabrication process and also introduce losses in the optical signal. Besides the radius value that was kept constant, the variable that was analyzed was the Bragg sensor positioning. Three Bragg layouts were considered relevant (Fig. 12).

All the samples had a similar mechanical behavior. As can be seen from Figs. 13–15, the load lines are very alike, presenting a slight difference in the first values due to the initial stretch state of the structure, which is not the same for all the samples. Also, a quick decrease at the fiber break instant can be seen in Figs. 14 and 15. The load decreases, momentarily, since there was no more fiber resistance. From this moment on, the resistance was only due to the PVC matrix and the load start to increase again until the collapse of the PVC matrix, which is not represent here

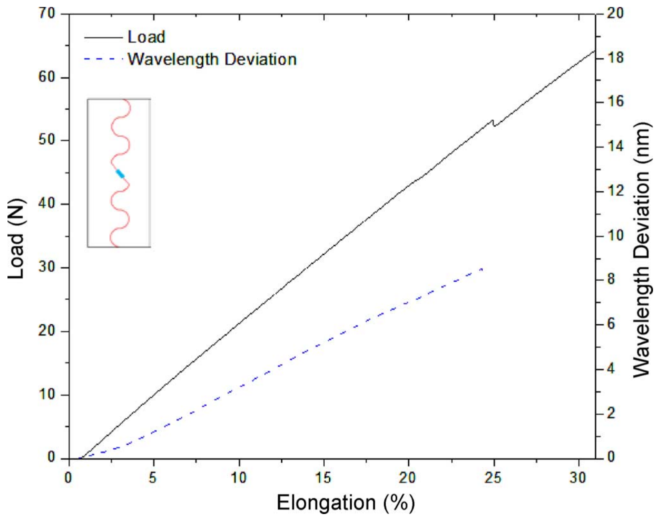

Fig. 14. Sensor response with the Bragg structure in a 45° angle regarding the elongation axis.

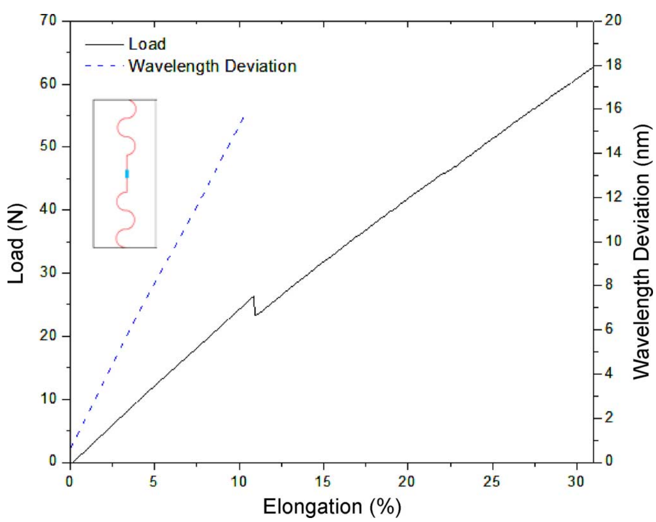

Fig. 15. Sensor response with the Bragg structure aligned with the elongation axis.

since there is no interest in measuring further on, as the optical fiber sensors were not operational anymore.

In terms of optical fiber sensor behavior, there are differences among the three sample types. The maximum elongation is dependent on the Bragg sensor positioning.

As can be seen, the sample with the sensor over the curve (Fig. 13) was the one that was able to reach a higher elongation (31%) than the other two. Meanwhile, the samples with the Bragg sensor aligned with the elongation axis (Fig. 15) reached the lowest elongation (10%). As the middle section is the region where the maximum stress is obtained, the curve sample had the layout that best dealt with that strain concentration.

The sample with the sensor aligned in the same axis as the applied load, was not able to deal, with such success, the mechanical requests, since its positioning does not allow the sensor a significant range of elongation for that specific area.

Another detail that can be seen is the linearity of the optical response. The straight line sample had a linear response due to Bragg sensor orientation, making it only sensitive to axial strain.

The sample with the sensor in a diagonal position (Fig. 14) also had a linear behavior as the one in straight line. Although, due to its orientation, its slope is lower when compared to perpendicular sample. The 45° angle made the sensor sensitive to the axial and perpendicular components of the structure behavior during the elongation. Consequently, the slope of Bragg response for this sample is low. Besides, this sample was able to sustain an elongation of 25%, thus presenting the best relation between sensor linearity and maximum elongation.

The curve sample (Fig. 13) was the one that was further from a linear response. This structure, in order to sustain the elongation, opens the curves during the stretching providing an elongation range. Although, its elongation is high, its behavior is more complex and consequently non linear.

With respect to the temperature component, the structure presented a response of 1.7 nm for a temperature variation of 100 °C. The same wavelength deviation would be obtained with 2.5% of elongation. For higher strain application proposes, the temperature influence can be neglected. However, for the opposite cases, the temperature influence must be taken into consideration. For these cases, at least two FBG need to be used which, one of them is free of strain, in order to measure only the temperature component and remove its influence from the strain data, or filtering may be used to separate both components.

V. Conclusion

A sensing smart structure based on the integration of FBG sensors in a polymeric foil, using standard industrial fabrication processes was designed. Fully functional prototypes were also developed and analyzed.

The initial structure requirements were fulfilled, taking into account the spread-coating process constraints and overcoming the restraints of the existing solutions.

No damage was detected at the prototype surface. The PVC matrix resulted in a very stable construction with a dimensional stability above 99%. From the optical response of the embedded sensor, the fabrication process did not present any change due to the integration process. The sensor was kept intact during the whole process. The overall structure showed a performance characterized by 0.8 pm per microstrain slope with a measurement range to 1.2 mm for a fully straight positioning of the FBG. Also, linear sensor response, spectrum shape maintenance during the load application, and measurements repeatability are features that were characterized.

A mechanical study was also conducted, considering the possibility of the structure application in nonhomogeneous surfaces, requiring an elongation capability. A diagonal positioning of the sensor allowed the sample to reach a maximum elongation of 25% with linear response, presenting the best committing between maximum elongation and linearity response.

The temperature influence may be a concern or not, depending on the magnitude of the strain and the temperature oscillations existent in the host structure. An elongation of 2.5% had the same wavelength deviation as a temperature shift of 100 °C.

The presented approach enabled a sensing solution that best fits the host structure and the monitoring systems requirements.

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