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Manufacturing Processes of Sensorial Materials: Sensors Placement and Experimental Validation

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Abstract. Nervous and sensorial materials are gaining more attention with in-material host of both sensors and actuators together to build functional materials for robotics and structural health monitoring. This paper presents a case study of a cantilever beam made with different materials including metals, polymers and powder-based materials using variety of manufacturing procedures with inserted sensors inside. The part becomes sensorial in this case and may be more functional for structural health monitoring and smart materials with dynamic functions. The results show that not only the location of the sensors is extremely important inside the material to capture true material's behavior, but also the integrity of both sensors and material that must be satisfied. Example with experimental validation have shown agreement between theoretical and measured values.

1. Introduction

Most materials can be turned into sensorial materials if the latter can host inserted sensors at the time of fabrication, or, at post fabrication. Actuators can also be added in the neighborhood of the sensors to build nervous materials [1]. A review of past techniques to embed sensors e.g. fiber optics (FBG), fiber PZT in materials has been carried out [2] showing possibilities to embed while manufacturing composite materials but little difficult to insert as a post process in metals e.g. Aluminum.

In particular, embedding FBG sensors into a polymer matrix is not a difficult process. The great potential of optical fiber sensors for the structural health monitoring was highlighted by Minakuchi and Takeda [3]. The authors reviewed research work mainly in Brillouin-based distributed sensing; and presented damage detection, life cycle monitoring and shape reconstruction systems applicable to large-scale composite structures. Luyckx and co-authors [4] provided an overview of some of the technical issues related to embedding sensors in composite structures. The output of an embedded FBG sensor was related to the strain of the structure through a monitoring scheme. In addition, the authors focused on temperature compensation methods when measuring strain with FBGs. In addition, embedding a combination of shape memory alloy wires and FBG sensors in glass fiber reinforced composites was investigated. More recently, the possibility to embed polymer optical fiber gratings [5] in composite materials was explored, and promising results were reported at temperatures and strains. Metallic materials remain widely used in many industries such as automotive [6] and aerospace [7]. Li et al. [8] explored the possibility to embed FBGs in aluminum and copper metal foils using ultrasonic welding processes and evaluated their sensing characteristics. The authors reported that it was not possible to embed the bare fiber in copper. This was attributed to the high hardness of copper. The



chemical plated fiber was embedded in aluminum; however, it was destroyed, because of the welding pressure, vibration and friction. The interesting method would be to have a sensor that almost naturally embedded at the subsurface or well inside at the time of manufacturing the part e.g. composite material, powder based materials or 3D printing with most materials ranging from metals to plastic [8, 9].

Embedding methods are various and challenging hence need more investigations. The embedding manufacturing processes vary depending on the material e.g. manual setting, gluing, and ultrasonic consolidation in plastic or metallic materials, powder based material with compaction followed by sintering, and rapid prototyping with laser sintering or 3D printing using polymer materials e.g. ABS, PLA. When the fiber optics are embedded inside materials e.g. plastic or metallic, the integrity has to be verified. Conditions of non-violation of integrity are on two levels; the sensors integrity when embedded in the host material, and the material integrity at the interface between the sensors and the host material [10]. Sensors placement in optimal places is important to properly recover data for various objectives e.g. to evaluate deformation and request to repair damage due to an unexpected impacting force on the structure. Consequently, this force needs to be identified in magnitude and location as part of structural health monitoring (SHM). Optimal sensors placement over a structure is one of the most active and interesting research for SHM. We are interested in the sensors placement within the material, but this can be initially at the surface, subsurface or inside at known depth.

The paper discusses corresponding manufacturing techniques for different materials to insert sensors at the subsurface of the material or in-depth in specific locations with a condition of sensors integrity and reliability in reporting material behavior.

2. Sensors location inside materials

While sensors deployment in host material is of importance, their local position becomes more important depending on the specific desired sensing needed in a particular position inside the material part. The offered local positions can be at various levels e.g. the surface, sub-surface or in depth inside the material.

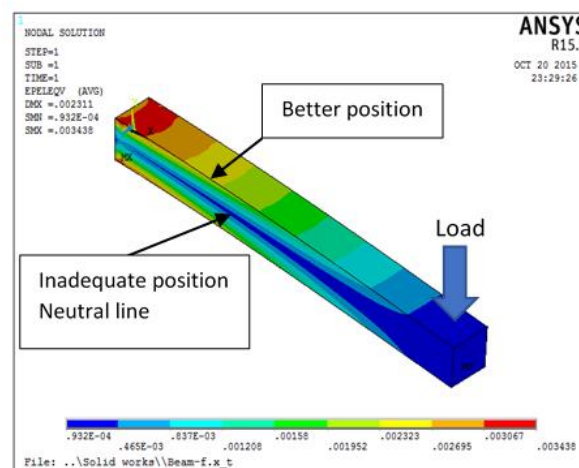


Figure 1. Sensor position suitable positions for strain measurement under bending condition.

This will depend on the type of sensing and where to capture sensing data. Temperature sensors can be placed anywhere in the material to collect temperatures while strain sensors are better placed at the surface or subsurface to collect strain away from neutral line, otherwise, no worth information will be recorded. Fig. 1 shows an example of strain distribution with better and inadequate positions of the sensors in bending cantilever. Embedding sensors inside the material needs careful attention depending on the host material and the type of the sensor. The corresponding embedding process is required. Recent tests have shown that embedding fiber optics can be easier in polymer, nylon but need specific manufacturing process for metals e.g. Aluminum [9].

3. Experimental tests

The purpose of inserting sensors inside materials is to turn them as sensorial materials capable of capturing true behaviors of any needed aspect depending on the application. This includes structural health monitoring and smart materials with dynamic specified behaviors for robotics and closed loop control. Hence, the integrity of the sensor and the material has to be verified to be able to report true information.

3.1. Embedding fiber optics in polymers

The purpose of the following experimental tests is to build a sample material with embedded fiber optic using 3D printing with the need to check both the material and the sensor integrity so that the material is not affected by the insertion of the sensors and the sensors are within the right operating conditions. The ABS filament is heat up at 250 oC using a standard 3D printing machine as shown in Fig.2. As the printing progresses, the placement of the fiber optics is manual. The fibers are lined up with the trajectory of the filament at the right position. The filling option in the 3D printer has to be high density to secure complete filling of the polymer without empty space.



Figure 2. a) 3D printing machine. b) ABS beam with embedded fiber optic.

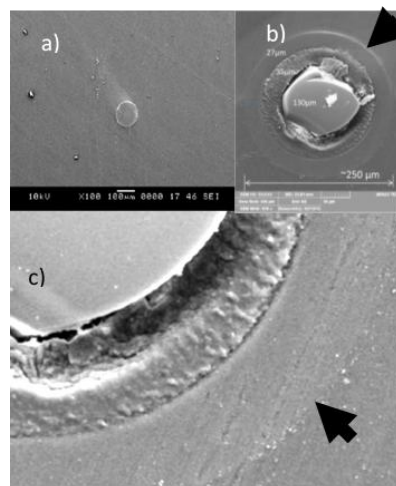


Figure 3. Cross section of the fiber embedded inside the polymer (Courtesy of Dr Khan).

To ensure reliable readings from fiber optics, the embedding of the sensors have to be well encapsulated and adhering to the material. This will allow the sensor to report the real behavior of the material surrounding it. By examining the SEM pictures of the cross section of the embedded fiber inside the printed polymer shown in Fig. 3, it appears that ABS material is firmly and completely adhering the surrounding the fiber outer jacket. The close picture in Fig. 3 d) shows a complete

melted material around the outer jacket of the fiber. To validate this observation, an experiment has been prepared with an aluminum beam having fiber optics embedded at the subsurface and having three Bragg sensors. All sensors are connected to data acquisition system run using national instrument interface.



Figure 4. Experimental setup for ABS beam.

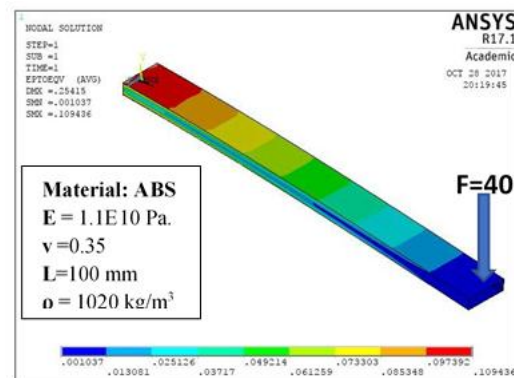


Figure 5. FEM simulation of the ABS cantilever beam.

Similar modeling and simulation of the ABS material has been carried out. The beam has been printed using ABS material and fiber optic with three FBG sensors. The fiber optic is added during the last passes of the printing head to finish the manufacturing. The beam is mounted with an applied load of 40 N at the tip as shown in Fig. 5. Strain measurements have been carried out and compared to FEM simulation as shown in Fig. 5. The comparison shows agreement between simulation and experimental measurements.

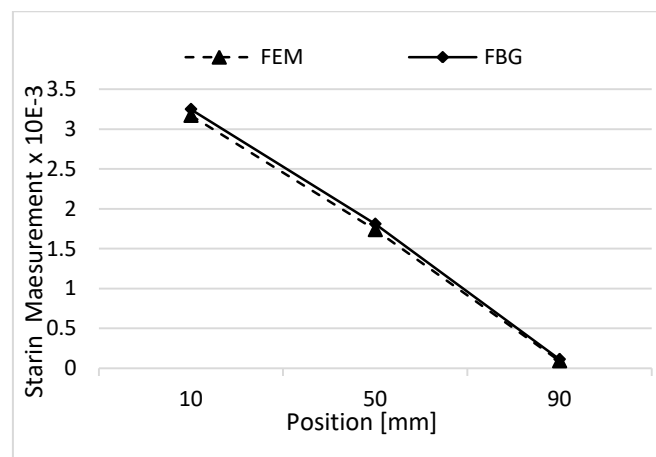


Figure 6. Strain comparison between FEM and fiber optic measurements in ABS.

3.2. Embedding fiber optics in metals

The fiber can be properly embedded inside a metallic structure at subsurface as discussed previously using two techniques; 1- gluing the fiber inside a slit cut on the metal, or 2- consolidate the fiber optic in the material using ultrasonic vibration followed by a small load on the fiber.

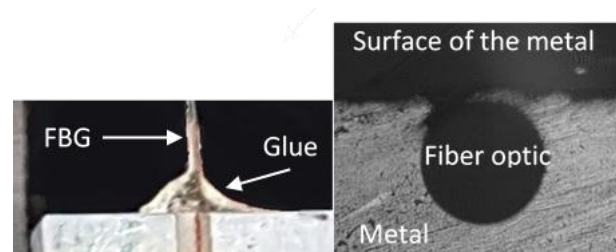


Figure 7. Fiber optic embedding inside Aluminium with glue or by Ultrasonic embedding.

Fig. 7 a) shows an example of the fiber optic glued in a manufactured slit on the surface, while Fig.7 b) shows embedded fiber optic using ultrasonic consolidation. The operating frequency was 20kHz, short wavelength within one second processing time. The host material was aluminum.

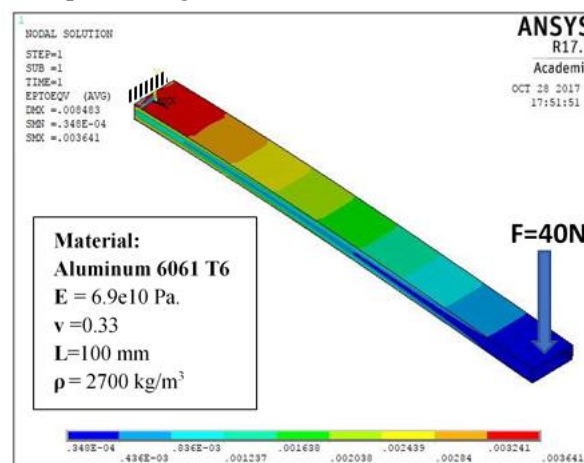


Figure 8. FEM simulation of the Aluminum cantilever beam.

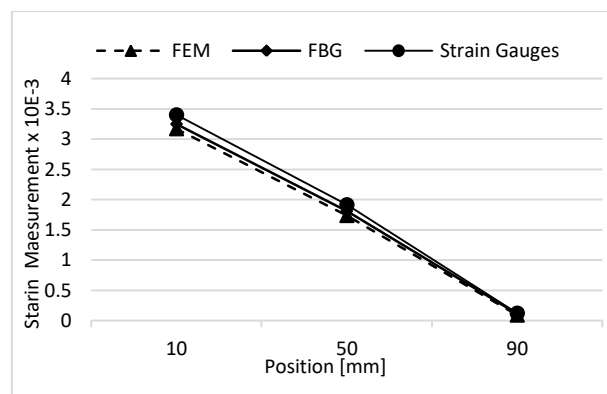


Figure 9. Strain comparison between FEM, fiber optic and strain gauge measurements.

To validate the measurement effectiveness of the embedded fiber optic Bragg sensors, an experiment has been prepared with an aluminum beam having fiber optics embedded at the subsurface and having three Bragg sensors. Three-strain gage sensors have been installed on the top of the FBGs sensors. All sensors are connected to data acquisition system using national instrument interface.

To be able to evaluate the measurements by the FBG sensors, the beam has been modeled and simulated by finite elements to compute the strain distribution at the surface over the length of the beam. A force of 40N is applied at the tip. The results are shown in Fig. 8. The comparison of the measurements from the strain gauges, FBGs and the simulation show good agreement as shown in Fig. 9.

3.3. Embedding carbon fiber sensors in polymers

Carbon fiber based material exhibits excellent mechanical properties and linear piezo resistivity behavior. Hence, it is used as a sensor that can measure strain for example. The fiber optic comes in various densities e.g. 1K, 3k, 5k, ...etc. We have selected 3K type of carbon fiber material that has been embedded inside ABS material, while printing a beam.

An experiment was carried out to compare the reading in deflection for an ABS beam with and without embedded carbon fiber. The beam is cantilever with rectangular cross section i.e. 12 mm width, 9 mm height and 100 mm length (Fig.10,11). The maximum deflection depending on the position over the length can be determined using Eq.1.

$$\gamma_{max} = PL^3/3EI \quad (1)$$

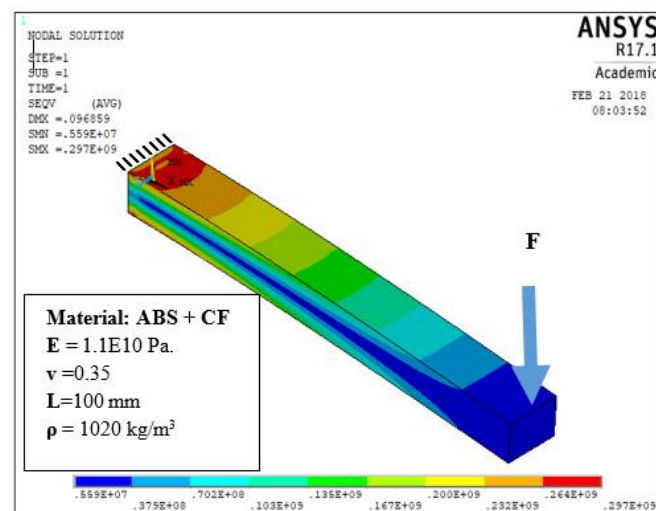


Figure 10. FEM modeling of the ABS beam and sample with embedded carbon fiber.

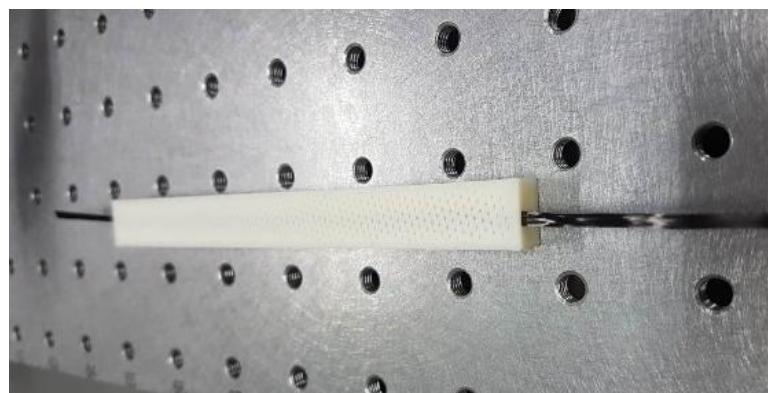


Figure 11. Sample with embedded carbon fiber.

Fig. 12 presents a comparison of deflection at the tip of the cantilever beam with and without carbon fiber inserted. Some discrepancy exists between beams. There is a slight effect of the carbon fiber of

type 3K added to the structure in bending. The beam is filled at about 90%. The carbon fiber needs specific installation to make sure the ports can read properly. These measurements have been done several times to reach the expected results.

The carbon fiber has been tested on its own to understand its behavior. It is known that the behavior is little different from the case where it is embedded.

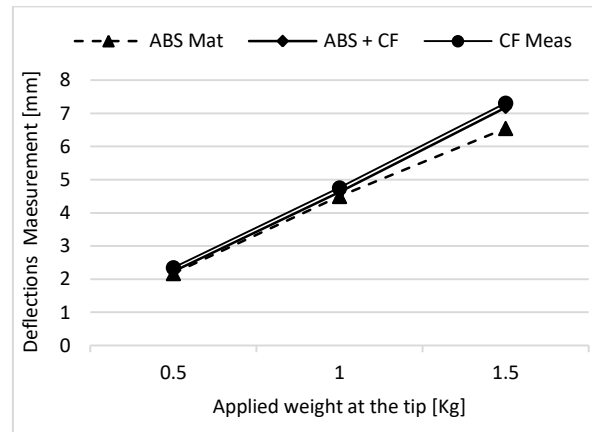


Figure 12. Deflection comparison between various cases.

4. Conclusion

This paper has shown that both fiber optic and carbon fibers seem to be very suitable to be embedded within a wide range of materials. Both sensors can be embedded while keeping their integrity safe. The host material builds a good sticking interface around the sensors which makes the data reading describing the parts behavior reliable. It is important to locate the sensors where useful readings are expected. This constitutes a good application for structural health monitoring and also robotic elements for precision handling or positioning under various shapes.

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