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DIRECTIONALLY SENSITIVE 3D PRINTED PIEZOELECTRIC SENSORS FOR STRUCTURAL HEALTH MONITORING

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ABSTRACT

This paper reports on advancement in the field of structural health monitoring (SHM) through the integration of fully 3D-printed piezoelectric sensors into composite materials. The sensors, based on polyvinylidene fluoride (PVDF), are manufactured using solvent-evaporation assisted 3D printing. In addition, a new shape of the sensor is developed to increase its directional sensitivity, improving the sensor's ability to accurately detect and monitor strain variations within the structure. This innovation takes advantage of the flexibility offered by 3D printing, allowing for the creation of sensors that can be adapted to different geometries, paving the way for potential industrial applications in the health monitoring of composite structures.

1 INTRODUCTION

Structural health monitoring (SHM) is essential for ensuring the safety and reliability of critical structures to detect damage or deterioration allowing for timely repairs and maintenance before it becomes a major safety hazard.[1] Recently , there has been a growing interest in the development of low-cost, lightweight, and easy-to-install sensors for SHM including strain gauges,[2] fiber-optic,[3] ultrasonic,[4] acoustic emission[5] or infrared[6]. Among the wide variety of sensors, polymer-based piezoelectric sensors have shown advantages of high sensitivity, wide working frequency range, flexibility, and durability.[7, 8] These advantages make piezoelectric sensors practical for SHM applications.

Polyvinylidene fluoride (PVDF) is a piezoelectric polymer known for its sensing properties along with biocompatibility and flexibility.[9-11] It exists in five molecular conformations, including the piezoelectric β-phase, which has a high net dipole moment. However, PVDF typically crystallizes in the non-piezoelectric α-phase, and can be converted to the β-phase via processing steps like stretching,[12, 13] annealing, or electrical poling.[14, 15]Studies have shown that 3D printing also allows PVDF to be mechanically stretched during printing, inducing a transition from the α- to β-phase,[16, 17].

The ability to combine the manufacturing of piezoelectric sensors with 3D printing of structural components opens up new possibilities for the design of smart and monitorable composite structures. PVDF sensors when printed along with the electrodes and embedded directly into the structure being monitored, allow to improve the sensitivity and resolution.[18, 19] Embedding sensors between the layers of composite laminae allows for precise monitoring in areas that are difficult to access otherwise for both maintenance and repair, further enhancing the reliability and

efficiency of structures. In addition, the versatility of 3D printing allows sensors to be produced in a variety of shapes and sizes, including linear, rectangular, serpentine, circular, and many others. 3D printing is also capable of fabrication of functional sensors by printing both electrodes and piezoelectric layers in the same process, thus, significantly reducing the time and cost of sensor production [20]. However, in many applications, such as embedding sensors in carbon-fiber fiber-reinforced polymers, the sensor needs to be electrically isolated from the conductive fibers using insulating materials to facilitate data acquisition.
To the best of our knowledge, no study has investigated the complete printing of piezoelectric sensors, including the insulation which is the route we explore in this study. To demonstrate the feasibility of this approach, we embedded a fully printed and insulated piezoelectric sensor in a composite material composed of two layers of prepregs and analyzed the signals measured by the embedded sensor by subjecting the composite to mechanical stress. Eventually, we designed and fabricated a strain gauge-shaped sensor capable of amplifying signals corresponding to the specific direction of mechanical deformation.

2 Material and Methods

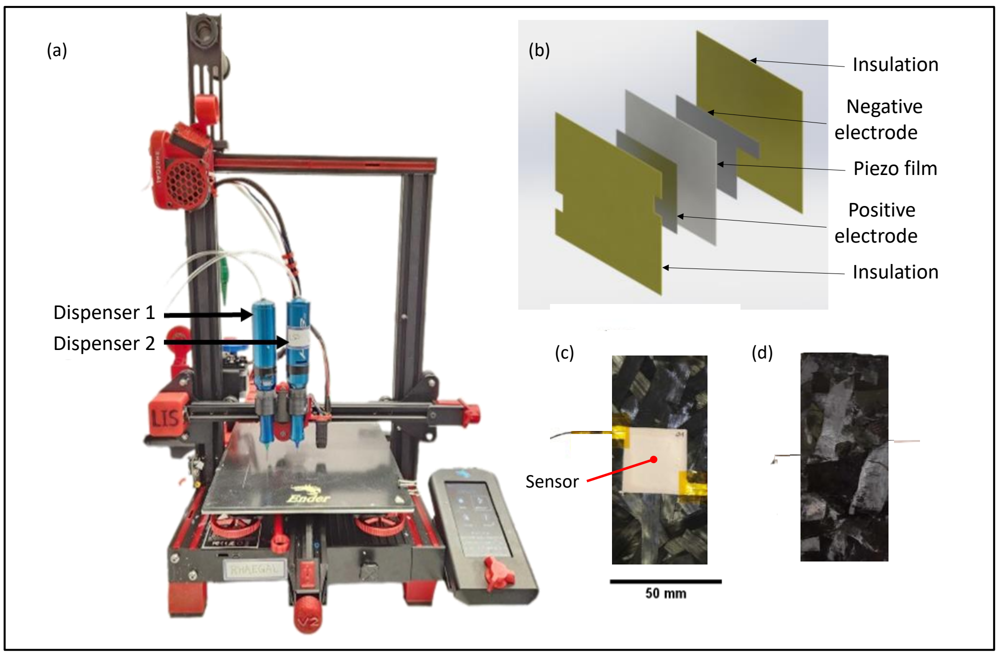

Figure 1: (a) Photograph of the 3D printer with multimaterial dispensing; (b) Schematic of the stacking sequence of the sensor, electrodes, and insulation; (c) Sensor placed on the first layer of the prepreg; (d) Sensor covered with second layer of prepreg before cure.

2.1 Ink preparation

Piezo-ink: 1.8 g of polyvinylidene fluoride powder (PVDF; Sigma-Aldrich), 0.2 g of barium titanate powder ($BaTiO_3$; 99.9% purity, 100 nm, tetragonal; Nanostructured & Amorphous Materials Inc) were poured into a ball milling container. To this mixture, 4 ml of dimethylformamide (DMF; Alfa Aesar), 0.6 ml of dimethylsulphoxide (DMSO;

Sigma-Aldrich; 65 g L^{-1}) and 6 ml of acetone were added and ball-milled (SPEX SamplePrep 8000, Series Mixer/Mill) with 3 zirconia beads (3.2 g each) at 1080 cycles per minute for 20 minutes.

Silver ink: Fast-drying silver paint (silver flakes suspended in iso-butyl methyl ketone, Ted Pella, Inc.) was used as conductive ink for printing the electrodes.

2.2. 3D printing of sensors

The piezoelectric ink solution was poured into a syringe barrel (3 mL; Nordson EFD) with a steel cylindrical nozzle (inner diameter= 0.25 mm; nozzle length = 12.7 mm; McMaster), which was placed into a pneumatically operated dispensing system (Ultimus V combined with HP-7X; Nordson EFD). The silver ink was poured into a separate syringe attached to a similar dispensing system. The two dispensing heads were mounted on a modified fused filament fabrication (FFF) 3D printer (Creality Ender 3 v2) as shown in Figure 1a. The deposition pattern was programmed using the Cura slicer. Dispensing pressures of 420 kPa and 21 kPa were used for the piezo and silver ink, respectively, with a deposition speed of 20 mm.s^{-1}. A schematic diagram of the stacking sequence of the sensor is shown in Figure 1b. The lower insulation layer was printed by depositing the piezo ink on the glass plate in the form of a square (35x35mm). The second layer was a silver square (25x25mm). The third and fourth layers were identical to the first and second, the third layer being the active piezoelectric layer. Finally, the last layer was printed again with piezo ink to form the upper insulation layer (35x35mm).

2.2 Drying

After printing, the sensors were transferred to a vacuum oven at 90 °C (10.1 kPa) for 24 h. The dried sensors after being peeled off from the glass plate possessed a final thickness of 0.150 +/- 0.010 mm.

2.3 Poling

The in-house poling station as used by Tao et al. [21], consisting of a heating plate, a silicone oil bath, and a voltage generator (ES60N-10W, γ High Voltage Research Inc), was used to pole the sensors. The electrodes of the sensors were connected to the voltage generator using alligator clips. The sensors were poled at 100 °C, 2 kV for 1 h. After 1 h, the heat was turned off but the voltage was kept on until the silicone bath temperature dropped to 60°C. The sensors were taken out of the silicone bath and washed with detergent to completely remove the silicone oil.

2.4 Embedding sensors into composites

Sensors were placed manually in between two sheets of prepreg (M77, Hexcel), as shown in Figure 1c-d. The composite was placed under a hot press (Enerpac) at 120°C for 8 min with a compression value of 58% of the initial thickness (≈ 4 mm).

2.5 Characterization

Piezoelectric charges generated by the sensors were converted into voltages using a charge amplifier (Piezo lab amplifier, MEAS Specialties) set in charge mode. Data acquisition was conducted with a NI-9239 system connected to a USB carrier NI-9162 (National Instruments). The acquired voltage data were then recorded and processed using a custom MATLAB 2021 interface.

3 RESULTS AND DISCUSSION

As shown in Figure 1c-d, the sensor was placed between two layers of prepregs and cured to obtain the smart composite. Using the compression test setup shown in the inset in Figure 2b, increasing values of pressures were applied to the fully printed all the sensors at a frequency of 1 Hz. Figure 2a shows the peak-to-peak amplitude obtained from the fully printed sensor before integration into the composite as a function of pressure. Figure 2b shows the peak-to-peak amplitude obtained from the fully printed sensor after integration into the composite as a

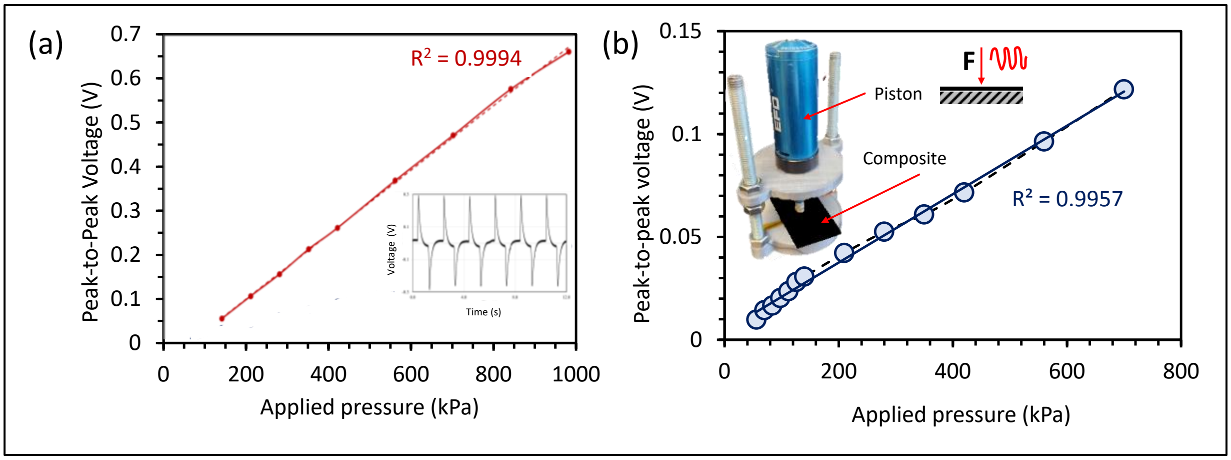

Figure 2 (a) Performance in dynamic compression (1 Hz) of the fully printed sensor before integration into the composite (inset: a typical sensor response vs. time); (b) after integration into the composite and the cure (inset: photograph of the custom-built compression testing system)

function of the pressure. Although the signal amplitude has decreased after the composite processing, the linearity of the sensor behavior is still maintained along with a sensitivity of 2e-4 V/kPa.

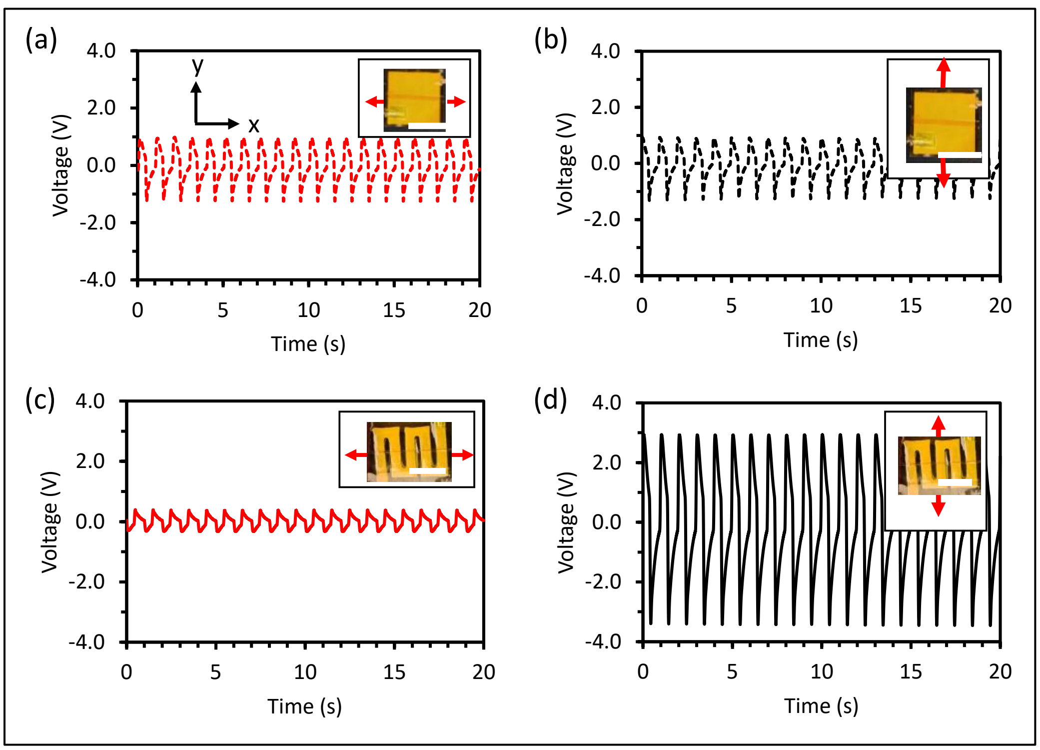

Figure 3: Comparison of the output signals from the square-shaped and strain gauge-shaped sensor when deformed along the horizontal x-axis (a and c) and vertical y-axis (b and d), respectively. Inset: Photographs of the sensors along with the direction of applied load (scale bar = 20 mm).

The square-shaped sensor although sensitive and linear after processing, cannot distinguish between the direction of the applied stress. As seen in Figure 3a-b, the square-shaped film sensors generate the same output voltage when pulled either in x- or y-directions. To take full advantage of the design flexibility offered by 3D printing and inspired by the strain gauge geometry, we fabricated zigzag sensors with strong directional sensitivity. When tested by applying the same cyclic tensile loading (4 MPa peak-to peak) at a frequency of 1 Hz, much higher output voltages were obtained when loading the sensor perpendicular to the zigzagging direction (y-axis) as compared to that along the zigzagging direction (x-axis). When stretched along y-axis, the peak-to-peak sensor voltage amplitude (~6 V) is 7.5 times greater than when stretched along the x-axis (~0.8 V). The tests were performed on three different sensors of the same geometry. Although all the sensors sensor exhibited similar behavior — producing a stronger signal perpendicular to the zigzagging direction— the amplitude varied from sensor to sensor. The curves shown in Figure 3c-d are representative of the overall results and captures the common characteristics observed across all units tested. Moreover, akin to traditional strain gauges, using two transducers forming a 90° angle between them would enable the determination of the direction of the force applied to the transducers or to the structure they will be integrated into.

This work presents a proof of concept of a single-step fabrication process of fully-3D-printed piezoelectric sensors with insulation. The sensors were then integrated into composite materials (laminates), and high-quality electrical signals were recorded from the sensor even after curing the composite. Furthermore, we developed directionally dependent sensors that, due to their shape, allow for greater sensitivity along a particular direction. Studies are still in order to quantify the reproducibility of the reported results, particularly regarding the signal amplitude ratio along the x and y axes in zigzag sensors. Moreover, optimization of the sensor integration into a composite, as well as understanding the effects of composite processing parameters (curing temperature, duration, etc.) on the sensor performance are necessary. Finally, further mechanical tests to quantify the degradation of the sensor's sensitivity during composite processing and use are in order. We believe that the sensors reported in this work bring us nearer to the potential industrial applications of all 3D-printed sensors, notably in the structural health monitoring (SHM) of composites.

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5 Conflict of interest

There are no conflicts to declare.

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