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Multi-Material 3D Printing of Highly Sensitive Flexible Multi-Layered Tactile Sensors

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Abstract. Additive manufacturing technologies like fused deposition modelling FDM 3D printing have become popular in academic research for their affordability and versatility. This paper presents a method for creating soft, multi-layered tactile pressure sensors with high sensitivity and a wide sensing range using FDM 3D multi-material printing. Combining conductive carbon black thermoplastic polyurethane (CBTPU), as the sensing material and polyvinyl alcohol (PVA), as the supporting material, allowed the fabrication of novel pressure sensors with enhanced mechanical compressibility and a wide electromechanical sensing range. For comparison, a solid sample of the same conductive material was fabricated and tested. The 3D-printed multi-layered model increased the sensor's compressibility by more than 6-fold compared to the solid sensor. This enhancement results in a greater change in electrical resistance by 9-fold. The multi-layered sensor showed repeatable behaviour in response to cyclic pressure suggesting their great potential for use in wearable electronics and robotic applications.

1. Introduction

Additive manufacturing, or 3D printing, is a technology that builds models layer-by-layer from computer-aided designs [1]. It offers many benefits such as reduced material waste and the ability to create complex structures via single or simultaneous multi-material fabrication [1]. Extrusion-based 3D printing like FDM uses thermoplastic materials that can be filled with functional nanomaterials to add properties like electrical conductivity [3-4]. These materials can be used to create flexible sensors that are suitable for wearable applications. Other thermoplastic materials such as water-soluble polyvinyl alcohol (PVA) can be 3D printed as scaffold support structures which can later be removed [4]. Tactile and pressure sensors are important for human-machine interaction, wearable electronics and soft robotics [2-3]. The flexibility of design offered by dual and multi-material 3D printing overcomes the constraints of conventional fabrication techniques [4]. Piezoresistive pressure sensors are popular for their flexibility and low energy consumption [5-6]. 3D printing techniques have been used to create these sensors, but precisely printing soft and flexible materials can be challenging [7-8]. Multi-material 3D printing has many advantages including the simple, rapid fabrication of pressure sensors without additional assembly steps [8-9]. As an example, dual-material FDM 3D printers have been used to create multi-axial force sensors with moderate sensing capabilities [9].

Here, this paper introduces the development of 3D-printed multi-layered resistive pressure sensors and their performance under compressive load. A novel method of dual-material 3D printing compressible multi-layered pressure sensors via extrusion-based FDM was presented. The layer-by-layer fabrication process and post-processing have been demonstrated throughout the paper. The physical properties of the materials were tested, and the electromechanical properties of the 3D-printed sensors were investigated.

2. Design and fabrication

As illustrated in Figure 1a the novel multi-layered pressure sensors were modelled using 3D CAD software. The design considered the accuracy of the FDM 3D printer as well as the flexibility of the sensing material. The design concept consists of suspended layers measuring 10 mm2 and connected at 2 corners. The interface corners measure 0.2 mm which creates a gap between each suspended layer. The pressure sensors were fabricated using a multi-material FDM 3D printing process as illustrated in Figure 1b. Carbon black thermoplastic polyurethane CBTPU was used as the sensing material and polyvinyl alcohol PVA was used as a dissolvable supporting material. An FDM with a dual extrusion system was used to print the CBTPU conductive sensing filament and the supporting PVA material simultaneously. At the beginning of 3D printing, 2 layers of conductive material measuring 0.2 mm thickness each were printed. Then, 2 corners were printed with the same CBTPU conductive filament to connect the lower conductive layer to the upper one. As the first extruder pauses, the void between the suspended conductive layers was filled with PVA-supporting material printed simultaneously using the second extruder. After printing, the PVA scaffold material was removed by immersing the sample in water for 24 hours and then drying it at 70°C for an hour as shown in Figure 1c. A solid sample measuring 10 mm2 was fabricated using the same 3D printing process, for comparison purposes. The solid sensor was made of a single, solid piece of the CBTPU material while multi-layered sensors were made up of multiple layers of the material with suspended gaps in between the layers.

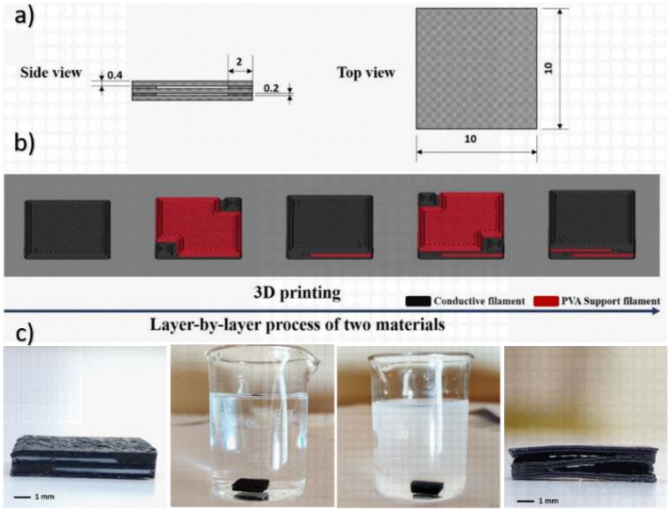

Figure 1 a) Schematic illustration of the side and top views showing measurements of the design (in millimeters), b) the 3D printing process uses a dual-extrusion system by alternating between 2 independent extruders each with a different material, and c) images of the model as 3D printed followed by the post-processing of dissolving PVA in water followed by an image of the sample dried and ready for use.

3. Results

3.1. Mechanical performance under compressive loading

The mechanical behavior of the multi-layered and solid sensors was evaluated by subjecting them to 100 kPa of compressive pressure as illustrated in Figure 2. The compressibility of the fabricated sensors was measured in compressive strain (%). When 100 kPa of pressure was applied, the solid sensor's compressive strain decreased to 1.5%. Whereas, the multi-layered sensor (with suspended layers) had a significantly higher compressibility of 9.84% when subjected to the same amount of pressure. When pressure is applied, the layers compress and the interface contact area between the layers is enhanced. The compressive pressure influenced the compression strain in the multi-layered sensor significantly as the strain compressibility of the multi-layered sensor was more than 6 times higher than that of the solid one.

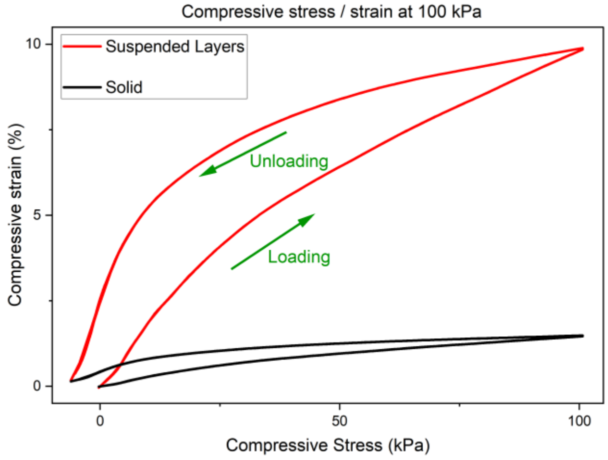

Figure 2. Compressive mechanical strain (%) to applied compressive pressure of 100 kPa.

3.2. Electromechanical results

After dissolving the supporting PVA material, the multi-layered samples had suspended gaps between the layers as illustrated previously above in Figure 1c. The structure's integrity was maintained due to the printed corners between the layers. The gaps which created the suspended structure were introduced to alter the samples' mechanical and electrical behaviour. The proposed suspended multi-layer design allowed for greater compressibility when pressure was applied as shown above in Figure 2. The change in electrical resistance of the multi-layered and solid samples was measured under compressive loading and illustrated in Figure 3. The change in electrical resistance of the 3D printed sensors was greatly influenced by the dynamic mechanical contact deformation. When compressive pressure is applied to the flexible pressure sensors, the conductive pathways within the sensing material are enhanced, leading to a decrease in electrical resistance. As pressure increases, the interface area of contact between suspended layers also increases. The higher the pressure, the more the sensor compresses and the larger the area of contact between the layers. As a result, a sharp change in electrical resistance was observed in the multi-layered sensor (with suspended layers) illustrated in Figure 3, compared to the solid sensor. As compressive pressure increased to 100 kPa, the change in electrical resistance decreased to -0.07 and -0.65 in the solid and multi-layered layer sensors, respectively. Interestingly, the change in electrical resistance of the multi-layered sample at 100 kPa was 9 times higher in comparison to the solid one. This was due to the layers in the multi-layered sample being forced closer together under compression, increasing the electrical conduction pathways and hence, significantly decreasing the electrical resistance.

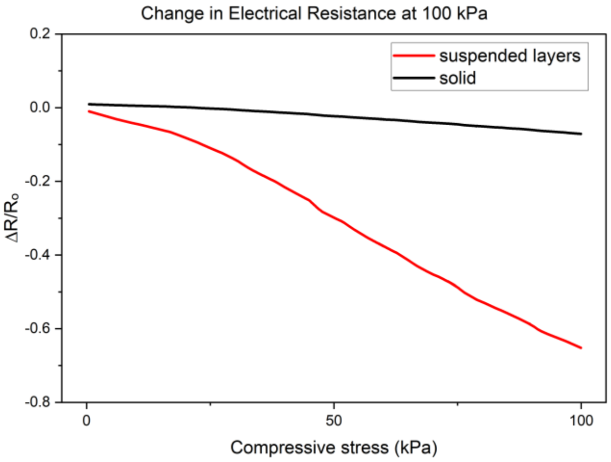

Figure 3. Change in electrical resistance of the first compressive pressure loading of the multi-layered and solid samples.

Cyclic loading was performed to compare the repeatability and reproducibility of the solid and multi-layered samples. Figure 4 shows the corresponding change in electrical resistance to 10 cycles of applied 200kPa compressive pressure. Both sensors showed repeatable and reproducible changes in electrical resistance to cyclic loading and unloading. However, the change in electrical resistance was much higher in the multi-layered sensor compared to the solid sensor under a 200 kPa compressive load. The solid sensor demonstrated moderately cyclic linear behaviour with the highest change in electrical resistance reaching -0.19. Whereas, the multi-layered sensor had a more significant change in electrical resistance, reaching an average value of -0.77. The change in the resistance value of the multi-layered sensor was more than 4 times higher than that of the solid sensor at 200 kPa. The difference in electrical resistance between the multi-layered and solid sensors was attributed to the fact that the layers in the multi-layered sensor were forced to pack more closely together under compression. This increased the electrical conduction pathways and decreased the electrical resistance sharply. The high compressibility and repeatable higher change in electrical resistance of the multi-layered sensor suggest that it is feasible to use the 3D-printed multi-layered design as a pressure sensor. A slight fluctuation was observed in the first 3 cycles of both sensors. This could be due to the elastic deformation of the CBTPU material and the rearrangement of the polymer chains to accommodate the applied pressure during the first loading-unloading cycles as illustrated in the loading and unloading previously above in Figure 2.

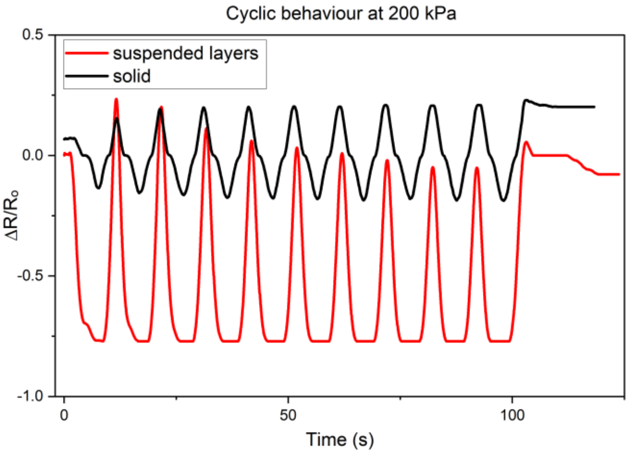

Figure 4. Change in electrical resistance of the multi-layered and solid samples under cyclic compressive pressure of 200kPa.

To demonstrate the capability of the 3D-printed multi-layered sensor, we further evaluated their electromechanical response to a broader range of applied pressures. To test its durability, we ran cyclic loading under compressive pressure ranging from as low as 10 kPa to 40kPa. As illustrated in Figure 5, the 3D printed pressure sensor exhibited very stable pressure sensing performance. The sensor showed pronounced electromechanical stability, which has been attributed to the suspended multi-layered design allowing from low to high-pressure values. It can be said that the sensor showed a distinct change in electrical resistance to various compressive loads suggesting its feasibility for wearable electronics and soft robotic applications [10].

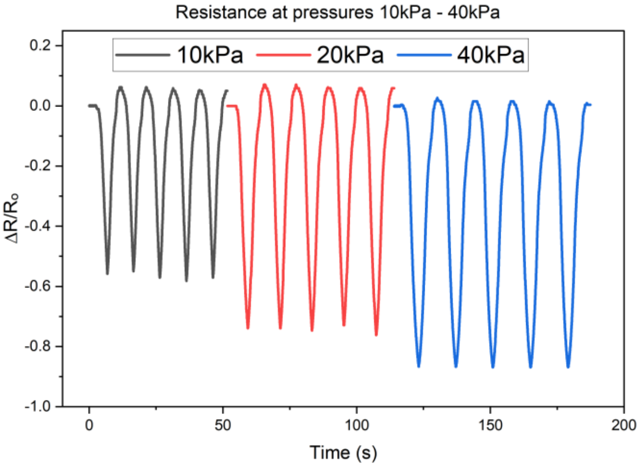

Figure 5. The change in resistance to a varying range of applied compressive pressure (kPa).

The pressure sensor's detection response and relaxation times were further analysed to investigate the sensing response to applied pressure. As illustrated in Figure 6, the sensor exhibited a fast response time to loading and unloading with response and relaxation times measured to 300 and 250 milliseconds (ms). The change in electrical response showed slight time dependence in the sensor's response to applied pressure.

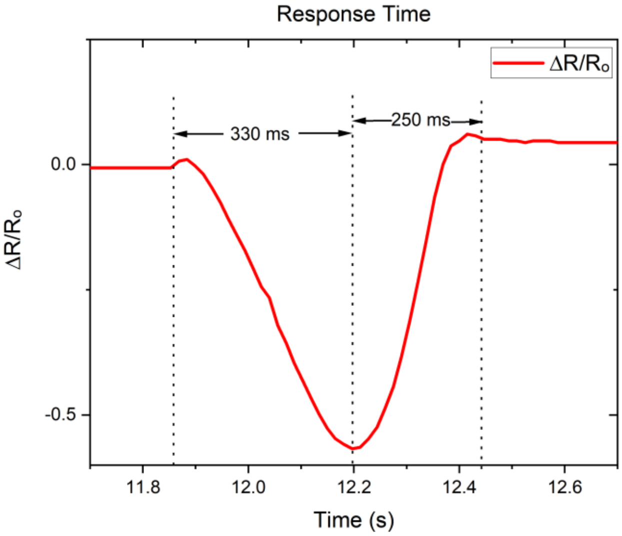

Figure 6. The calculated loading and relaxation response speed of the 3D printed sensor.

4. Discussion and conclusions

In summary, a method for creating flexible, compressible, multi-layered tactile pressure sensors using multi-material 3D printing was presented. An extrusion-based FDM technique was used to print the conductive sensing filament and the supporting PVA scaffold material simultaneously. Multi-material 3D printing allowed for the rapid fabrication of pressure sensors without additional assembly. This was achieved through the simultaneous printing of active sensing material and sacrificial material in a one-step process. The scaffold material was dissolved in water, leaving suspended multi-layered pressure sensors. The mechanical and electrical properties of the 3D-printed sensors were evaluated. The design of the multi-layered pressure sensor using conductive elastomer simultaneously 3D printed with PVA as scaffold support material enhanced the sensitivity and sensing range of the 3D printed pressure sensor. The flexibility of 3D multi-material printing allowed for the creation of novel tactile sensors that outperformed the solid one made of the same conductive material. The multi-layered suspended design enhanced the mechanical compressibility of the pressure sensor by 6-fold. This enhancement consequently improved the change in electrical resistance by 9-fold in comparison to a solid one. The 3D-printed sensors were tested for their cyclic mechanical and electrical properties and showed good stability and reproducibility with minimal hysteresis. The sensors were able to respond rapidly to a wide range of pressures suggesting their feasibility for wearable electronics and soft robotic applications.

5. References

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