MECHANICAL SENSING TOWARDS 3D-PRINTED WEARABLES

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ABSTRACT

This paper demonstrates the potential of combining two recent technological advances: 1) wearable mechanical sensors and 2) 3D printing processes accessible to a wide range of users. We suggest that compliant, textile-like wearable sensors that are fabricated in easy-to-access processes, like desktop 3D printing, will empower a wide range of users to design, fabricate, and prototype wearable sensors. We characterize the electrical and mechanical properties of a conductive, 3D-printed textile. The electrical and mechanical properties are tunable with the selected print settings, with a gauge factor of greater than 13 in one sensor type.

Keywords – wearable sensor, strain sensor, 3D printing, additive manufacturing

INTRODUCTION

Wearable sensors have been proposed for applications such as human-machine interfaces [1] and health monitoring [2]. Many commercially available wearable devices, such as fitness or step trackers and smart watches, are relatively stiff or contain rigid materials. Researchers have expended significant effort to fabricate sensors embedded in cloth or rubbery materials; many of these fabrication processes require fume hoods or specialized equipment. Some notable exceptions to lab-based fabrication processes include printing conductive ink onto clothing [3] and fibercraft with conductive yarn or thread [4]. While these processes empower users to fabricate wearable sensors at home or in makerspaces, specialized tools may still be required to achieve precise sensor placements and repeatable performance.

Innovations in 3D printing have spurred interest in devices beyond solid forms, including flexible materials [5], 3D printed textiles [6, 7], and 3D printed sensors [8, 9]. A common fabrication approach for 3D printed flexible sensors is to print the conductive layer(s) on top of or embedded within a flexible substrate such as silicone [10]. While these works are major steps towards seamlessly wearable sensors, they require custom fabrication equipment and significant user training or advanced materials for the substrate or conductive layers [2, 11].

This work demonstrates a 3D printing process towards textile-like wearable sensors. In contrast to flexible filament 3D printed sensors, the process uses only commercially available filaments in an unmodified fused deposition modeling (FDM) printer. The resultant material — defeXtiles [12] — is mesh-like, compliant, and its properties are tunable with print settings. To demonstrate defeXtile's applications towards wearable sensors, we characterize its electrical and mechanical responses when printed using conductive PLA.

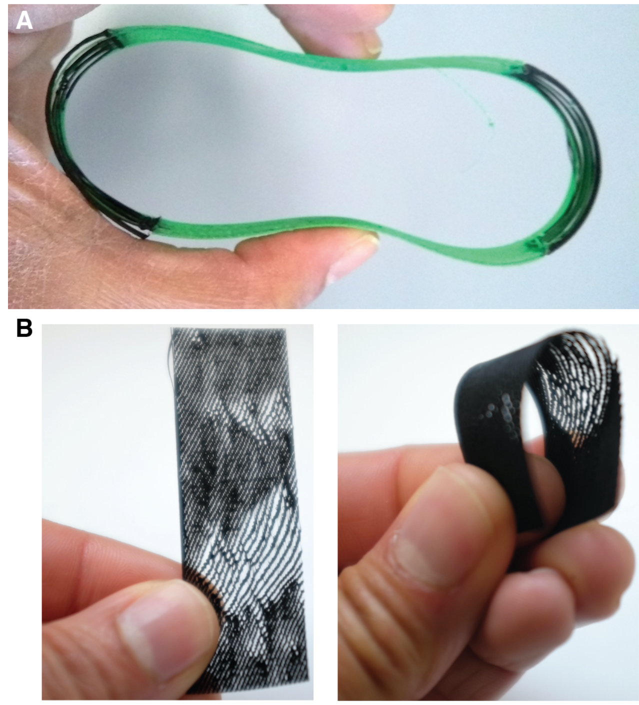

Figure 1: Photographs of defeXtiles samples. (a) A multi-material band with standard PLA (green) and conductive PLA (black). (b) A conductive sample with extrusion multiplier (EM) = 0.4.

DEFEXTILES FABRICATION AND SENSING

Defextiles are fabricated by reducing the extrusion multiplier (i.e., the fraction of material extruded by the print head) in the slicer software during 3D printing. The printed material is a network of thin "threads" between "posts" of larger deposited material. The print's flexibility arises from the mechanical compliance of the threads rather than the use of a flexible filament. In contrast to other flexible prints that print a single layer onto the bed, this approach enables more complex, 3D structures. Fig. 1 is a series of photos with defeXtiles samples. Fabrication process details are available in the Materials and Methods section.

The mechanical properties of the material and thread size are tunable through the extrusion multiplier (EM) and the print head speed settings [6]. Photographs of conductive PLA samples printed with EM of 0.3, 0.4, and 0.5 are presented in Fig. 2 with inset optical micrographs. The sample with an EM of 0.3 has a visible network of posts and threads, while the sample with an EM of 0.5 is almost entirely opaque. The thread diameters are approximately 35 μm and 100 μm for the 0.3 and 0.4

EM settings, respectively. The samples with EM of 0.5 have a high enough material extrusion that individual threads are not visible, and the structure similar to a solid print. The thickness of the sample at the posts is approximately 400 µm, which is determined by the nozzle size of the printer.

Using a multi-material 3D printer, both standard and conductive PLA may be deposited to form sensing and structural regions of a print. Due to the brittle nature of the conductive PLA, the extrusion multiplier typically needs to be higher (e.g., EM > 0.3) than for standard PLA (e.g., EM > 0.2) for the print to be successful. Fig. 1a is a photograph of a two-material band of defeXtiles, with standard PLA in green and conductive PLA in black.

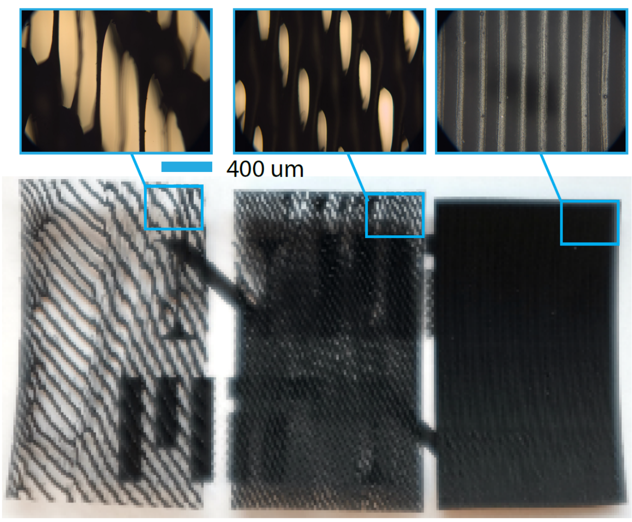

Figure 2: Photographs of conductive PLA defeXtiles samples with varying EM. Insets: Optical micrographs of conductive defeXtiles samples.

Wearable mechanical sensors must simultaneously withstand typical forces experienced during operation while demonstrating high sensitivity. In piezoresistive materials, reversible response to mechanical deformation occurs with changes in 1) the material dimensions; 2) the material conductivity, such as contact between conductive particles in an insulating matrix; or 3) electrical contact between structures.

Resistive approaches, rather than inductive or capacitive, are best suited to defeXtiles because the material has a sheet resistance in the 1 kΩ/sq range. In defeXtiles, similar to many textiles, the material is flexible out of plane but stiff in plane as planar deformation exerts an axial force on the threads. As such, the conductivity of the material under deformation can change in a few ways: the deformation can change the thread geometry, the deformation can cause delamination between printed layers of the material, and the deformation can modify conductivity within the PLA.

RESULTS

The average and standard deviation of sheet resistances for five samples of each EM are displayed in Table 1. The unstressed resistance of a sample ranges with EM. Samples with an EM of 0.3 have the largest sheet resistance, while samples with an EM of 0.5 have the smallest.

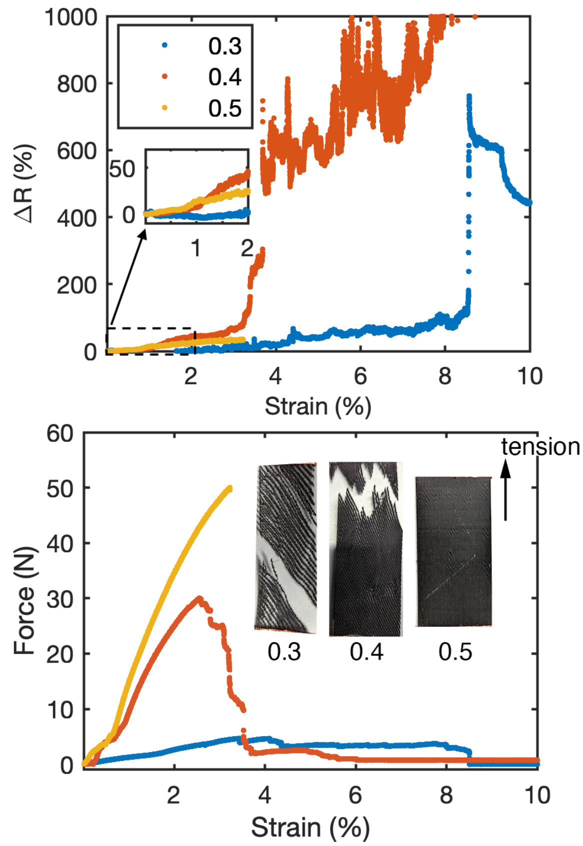

Figure 3: Resistance (top) and force response (bottom) to tension during one cycle of loading to failure. A representative sample of each EM is included.

Fig. 3 illustrates the response of each EM to tension. The 0.5 EM sample had the largest stiffness and was able to tolerate forces of 50 N, at which point the test was stopped. The 0.3 EM sample is most compliant and has the lowest initial sensitivity. Above strains of 1%, the resistance of each sample increases by a percentage of greater than 50 before the samples begin to tear. The force-tension curve illustrates these partial tears (e.g., EM of 0.4 at 2-4% strain), and the samples after the test are shown with the inset photographs. The average and standard deviation in maximum force and tensile gauge factor (GF) (i.e., the ratio of the resistance change to the applied strain) at a tensile strain ε of 1% is presented in Table 1 ($N = 5$).

Fig. 4 is a plot of three representative samples under compression along the length of the sample. The material buckles, mimicking increasing curvature with compression. After test completion, some curvature was observed in the samples, indicating plastic deformation. The resistance of the material in

Table 1: Mechanical and electrical properties with EM (average ± one standard deviation).

Property	0.3	0.4	0.5
Resistance (kΩ/sq)	5±0.34	0.74±0.06	0.44±0.06
Max Tension (N)	3.0±1.0	33.8±6.9	>50
Tensile GF ($\Delta R/\varepsilon$)	4.0±5.7	11.7±5.2	13.3±5.1
Compressive ΔR (%)	-3.6±1.7	-2.9±1.9	1.3±2.4

the 0.3 and 0.4 EM samples was lower after testing, while the 0.5 EM sample increased slightly in resistance during the test but returned to its initial value when the test was complete. The average resistance change and standard deviation for a compression of 2.4 mm, which corresponds to a curvature of approximately 0.8 cm^{-1}, is shown in Table 1 (N = 5).

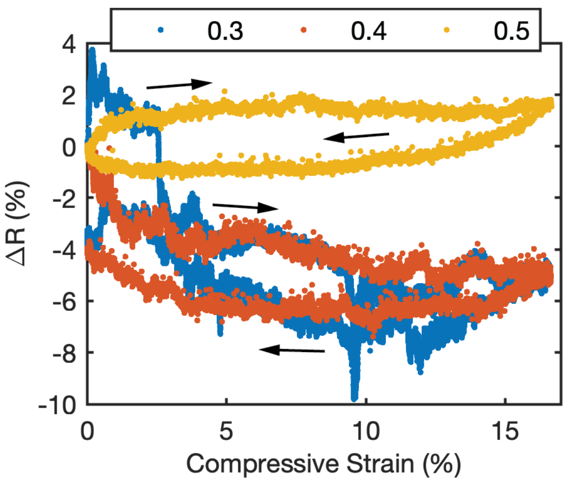

Figure 4: DefeXtiles response to compression and buckling. A representative sample of each EM is included.

DISCUSSION

The mechanical and electrical responses of the defextiles samples vary with EM, and the 0.5 EM samples show the smallest device-to-device variation. In the tensile tests, the resistance increased in all samples, although variations between EM and from sample to sample were present. At small strain, the resistance increase may result from a simultaneous increase in thread length and increase in piezoresistivity of the conductive PLA. If the applied strain were not sufficiently large to cause plastic deformation, the response may be recoverable, enabling the sample to behave as a repeatable mechanical sensor (e.g., strain below 1%).

The largest response to tension occurs when the threads plastically deform or the structure tears, beyond 2% strain. This approach to mechanical sensing is not repeatable due to irreversible changes in the material. However, it does support the use of defeXtiles as conductive layers for signal routing within a wearable device, because the resistance is relatively stable with small deformations. In the 0.3 EM samples, for example, the resistance change is low until the sample begins to tear, because the threads are compliant and can plastically lengthen without large increases in resistance.

In the buckling experiments, the sample with EM of 0.5 showed a small but recoverable change in resistance, while the 0.4 and 0.3 samples showed lower final resistance. The lower final resistance suggests a compressive stress on some part of the material, along with a decrease in piezoresistance. Similarly to the tensile strain experiments, this response might be recoverable at smaller deformation.

When considering sensor design with this material, a tradeoff exists between the mechanical compliance (which is desired for textile-like prints), the sample-to-sample variations (which increase as EM decreases and the post and thread network becomes less ordered), and the electrical properties (higher sensitivity and lower resistance with higher EM). Sensors and conductors may need to be higher EM, while lower EM materials can be used only as an aesthetic or display component, for example to electrically connect LEDs. Using conductive PLA, which is relatively rigid and brittle when compared to other plastic filaments, the defeXtiles fabrication process is best suited to creating conductive, compliant layers or investigating other sensing modalities such as capacitance or layer-to-layer resistance.

CONCLUSIONS AND FUTURE WORK

This paper introduced a 3D-printed conductive textile material and demonstrated the material's applications to conductive wearable sensors. This process makes it possible to fabricate mechanically and electrically tunable materials and multimaterial structures using hobbyist materials and equipment, making it a promising approach for "democratizing" access to wearable mechanical sensors. Additional characterization and fabrication effort is required to design robust structures with both standard and conductive PLA, understand sources of electrical and mechanical variation within the selection of extrusion multiplier, and develop strategies for increasing mechanical robustness while maintaining flexibility. Using materials other than PLA such as flexible filaments or highly conductive filaments may also enable more sophisticated sensor designs, such as capacitive or resistive sensors with the ability to tolerate large deformations. Future work will include demonstrating devices with multiple sensors and presenting practical applications of the sensors to health monitoring and human-machine interfaces.

MATERIALS AND METHODS

A Flash Forge Creator Pro 2 with dual nozzles was used for all prints. Parts were sliced using Simplify3D and printed at a speed of 3600 mm/min as a ring with 20 mm height and 8 cm diameter. Before printing, the global height between nozzle and bed was decreased by 150 µm from the leveling step to allow the material to adhere to the bed. Conductive structures were printed with using ProtoPasta conductive PLA (T = 220 °C, EM = 0.7) and standard PLA structures were printed using Hatchbox PLA (T = 220 °C, EM = 0.4), with a bed temperature set to 40 °C. After printing, the defeXtiles rings were cut into

60 mm × 20 mm strips and annealed by placing into an oven heated to 60 °C which was allowed to cool to room temperature over 3 h. After annealing, the end of each sample was wrapped with copper tape, which served as electrodes. The copper tape was coated with a thin later of hot melt adhesive to provide additional adhesion during mechanical testing and to electrically isolate the samples from the materials testing system.

Resistance during mechanical testing was measured using an NI-6002 USB data acquisition board and voltage divider, and sheet resistance was measured with a benchtop digital multimeter (BK Precision 5492B). Samples were loaded into a materials tester (i-Test 2.5, Mecmesin), gripped with a set of pneumatic grips, and strained at a rate of 2 mm/min for the tension tests and -2 mm/min for the compression tests. Tension tests were terminated when the load reached 50 N or the extension reached 10 mm, while compression tests displaced to -10 mm and returned to 0 mm.

ACKNOWLEDGMENTS

The authors would like to thank Dr. H. Hochsztein for guidance with mechanical test equipment.

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