Research on flexible sensor based on 3D printing manufacturing by fused deposition molding

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Abstract. A flexible capacitance and resistance sensor is studied, which is manufactured by single step using 3D printing technology of fused deposition molding. Compared with the existing manufacturing technology of flexible sensor, the 3D printing technology has the advantages of low manufacturing cost and simple manufacturing process. The capacitive force sensor and the resistance temperature sensor are fabricated by melting deposition and forming 3D printing respectively using the wires of conductive and dielectric materials. The capacitive force sensor adopts parallel plate structure, and its relative sensitivity can reach 0.088% / N. The relative sensitivity of the resistance temperature sensor can reach 2.2% / °C. The resistance and capacitance sensors can be used as touch sensors, which have great potential in the fields of electronic skin, intelligent wearable devices and soft robots.

Keywords: Fused Deposition Molding, 3D Printing, Flexible.

1. Introduction

3D printing technology has been widely used in manufacturing various types of flexible sensor components, such as detection electrode, micro antenna and pressure sensor. The advantage of 3D printing technology in manufacturing sensor components is that each part of the sensor components (substrate, electrode, active components) has the single printing technology to manufacture independently, and there is no need for tedious assembly process. Specifically, the main application of 3D printing technology, such as ink-jet 3D printing and squeeze printing. Leigh et al. Proposed to manufacture a switch type flexible sensor using fused deposition 3D printing technology [8]; their research results effectively proved the feasibility of manufacturing piezoresistive and capacitive force detection devices by fused deposition 3D printing technology; although it can be considered to be completely printed, the final device only provides a binary behavior, just like an open circuit Off.

In this paper, we study a method of manufacturing flexible sensors by FDM 3D printing. Using a single FDM 3D printing manufacturing technology, we realize the manufacturing of flexible capacitive force sensors and resistive temperature sensors. The relative sensitivity of these sensors is obtained by experimental measurement, and the interaction between materials in the process of FDM 3D printing is studied, And the electrical characteristics and thermomechanical properties of the sensor manufactured by the method. Finally, we show the monitoring function of the flexible sensor.
2. Manufacture of flexible sensor

The flexible sensor is made of two different polymers: one is soft thermoplastic polyurethane (TPU) and the other is semi-rigid polylactic acid (PLA) doped with carbon powder, which is mainly used as conductive electrode and thermal resistance sensing element. In this paper, we choose the above two materials to make the flexible sensor mainly based on the following three aspects: (1) thermoplastic polyurethane and carbon doped polylactic acid are widely used in fused deposition molding 3D printing, and the technology is very mature; (2) their low cost is conducive to a wide range of promotion; (3) they have very high biocompatibility. Thermoplastic polyurethane (TPU) has been widely used in the preparation of flexible devices. It has excellent yield capacity and its elongation can reach 65%. At the same time, considering the yield elongation of 2% relative to the neutral plane and the maximum bending radius, through reasonable design, PLA can be used to make flexible devices. The yield elongation of PLA doped with carbon powder is slightly higher than that of pure PLA due to the formation of network structure. In this paper, in order to ensure that the structure of PLA doped with carbon powder works normally, the radius of curvature should be more than 5 cm. At the same time, considering the curvature radius and yield limit, the thickness of the structure is less than 1 mm without external wrapping.

In this paper, the high-end desktop 3D printer ultimaker S5 is used to make flexible sensors, which can print various types of polymer materials. The theoretical resolutions of X, y and Z axes of ultimaker S5 are 350 μm, 350 μm and 60 μm, respectively. Limited by the physical properties of printing materials such as viscosity and capillary force, the maximum roughness of TPU structure is 40 μM. In the printing process, by increasing the printing temperature, the viscosity of TPU and PLA doped with carbon powder can be effectively reduced, so the capillary force will exceed the viscosity force to obtain a flat layer without micropore; in addition, during the printing process, the heat of high-temperature printing nozzle will diffuse in the printed material layer, which is conducive to TPU and PLA doped with carbon powder the fusion of materials. However, in this case, due to the low viscosity of the printed material, it will diffuse along the substrate or printed material layer, resulting in the increase of printing resolution. By adjusting printing parameters such as printing temperature, printing speed and printing layer thickness, we can get a compromise between resolution, printing speed, thermal diffusion and viscosity. Another feature of ultimaker S5 is that it can realize multi material printing, that is, it can automatically switch between different printing materials in the printing process. Therefore, in this paper, the manufacturing of flexible sensor is realized in the same printing process, without additional device docking and assembly process.

3. Results and analysis

The resistance of the printed PLA material doped with carbon powder mainly depends on the raw material and printing process. It is obvious that the higher the concentration of doped carbon powder, the better the conductivity; secondly, the printing process will also affect the conductivity, such as the line width, the number of layers and the heat diffusion in the printing process. In this paper, bone type flexible film resistors with length, width and thickness of 15 mm, 5 mm and 300 μm are fabricated, and terminals for external power connection are added at both ends of the film resistor. It is found that when the direction of the printed line is the same as that of the current, the thermal resistance of the flexible film is the smallest; if the direction of the printed line is perpendicular to that of the current or is 45 degrees, the thermal resistance of the flexible film increases about 30%.

In order to test the reliability of thin film resistors and obtain the optimal value between stability and flexibility, thin film resistors with thickness ranging from 120 μm to 300 μm are fabricated and measured. When the thickness of the film resistor is 300 μm, the conductivity of the resistor is the best, but the softness is poor. Through the test of 10 samples, the average value of resistance is 16.17k Ω / cm, and the standard deviation is 0.89k Ω / cm.
The sensitivity coefficient of the flexible film resistor is obtained by printing the flexible film resistor with bone structure on a 600 μm thick thermoplastic polyurethane substrate. The selection of 600 μm TPU thick substrate is the result of considering the structural stability, softness and ensuring that the yield elongation of PLA doped with carbon powder is in the effective range. The thickness of thin film resistor is 60 μm, 120 μm, 180 μm and 240 μm, respectively. When the bending radius of the flexible film resistor reaches 2.5cm, the strain of the flexible film resistor with thickness of 60 μm and 240 μm is 2.6% and 3.3% respectively. When the external force is unloaded, the resistance values of various specifications of thin film sensors basically remain unchanged, which means that the flexible film resistor with thickness of 180 μm will not have plastic deformation after 3% tensile strain. Finally, the strain coefficient of the thin film sensor is 6.89 and the standard deviation is 2.45.

A series of parallel plate capacitors were fabricated based on fused deposition molding technology. The capacitors have the same electrode area and electrode thickness (100 μm), but different dielectric thickness, including 200 μm, 400 μm, 800 μm and 1000 μm. All the capacitance values are in the range of PI farad (PF), and show excellent stability under the condition of voltage value of 1 V and frequency of 1000 Hz.

According to the theory, the capacitance of the capacitive sensor will decrease with the increase of the thickness of the dielectric layer. However, with the increase of the thickness of the dielectric layer, the dielectric constant will decrease. As mentioned above, during the heating process, the heat from the nozzle is transferred to each layer of the capacitive sensor, which mixes two different materials (i.e., dielectric and conductive materials) to form a new layer, which will affect the dielectric constant. The smaller the dielectric thickness is, the stronger the effect will be. It is found that the average value and standard deviation of the dielectric constant of the sample with 1000 μm thick dielectric layer are 7.37 and 0.34 respectively. Compared with the sample with 200 μm thick dielectric layer, the average value and standard deviation of the dielectric constant are 10.03 and 1.35 respectively. The functional relationship between the change rate of relative capacitance and the external force is obtained by using a vertical piston type material testing machine. The purple continuous curve represents the theoretical value obtained by the mathematical model, the dotted line is the test value of the sample for four times, and the maximum loading force is 50 n. For the capacitive sensor with 1 cm2 electrode area, the relative sensitivity coefficient is 0.083% / n. By testing 57 samples, the average value of relative sensitivity coefficient is 0.088% / N, and the standard deviation is 0.016% / n. For the capacitive sensor with 2 cm2 electrode area and 400 μm dielectric layer thickness, the average capacitance is 857 FF and the average dielectric constant is 9.68, which is consistent with the above analysis.

4. Conclusions
In this paper, the parallel plate structure capacitance and thermal resistance flexible sensor is fabricated by melt deposition 3D printing technology. The flexible sensor is fabricated by a single printing technology deposition of multi-layer thermoplastic polyurethane and carbon doped polylactic acid material. The mechanical and electrical properties of the sensor are affected by the melt deposition process, that is, the interaction between the nozzle and the material can change the resistivity and dielectric constant of the sensor. For the capacitive force sensor, it is found that the relative sensitivity is 0.088% / N, which is consistent with the theoretical value of the mathematical model, and has uniformity under different media thickness. The thermal response of the resistance sensor is higher than the mechanical response, so it can be used as a temperature sensor. In this paper, the basic knowledge of multi parameter and flexible integrated fused deposition 3D printing sensor is studied, which has broad application prospects in the field of soft robots and wearable devices.

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References
[1] Costa J C, Spina F, Lugoda P, et al. Flexible sensors—from materials to applications [J].
Technologies, 2019, 7 (2): 35.

[2] Lu N, Kim D H. Flexible and stretchable electronics paving the way for soft robotics [J]. Soft Robotics, 2014, 1 (1): 53 - 62.

[3] Adams J J, Duoss E B, Malkowski T F, et al. Conformal Printing of Electrically Small Antennas on Three-Dimensional Surfaces [J]. advanced materials, 2011, 23 (11): 1335 - 1340.

[4] Leigh Simon J, Bradley Robert J, Purssell Christopher P, Billson Duncan R, Hutchins David A. A simple, low-cost conductive composite material for 3D printing of electronic sensors. [J]. PloS one, 2012, 7 (11).

[5] Yao S, Zhu Y. Wearable multifunctional sensors using printed stretchable conductors made of silver nanowires [J]. Nanoscale, 2014, 6 (4): 2345 - 2352.

[6] Xiao J, Gao Y. The manufacture of 3D printing of medical grade TPU [J]. Progress in Additive Manufacturing, 2017, 2 (3): 117 - 123.