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Screen-printed piezoelectric shoe-insole energy harvester using an improved flexible PZT-polymer composites

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Abstract. This paper reports improved screen-printed piezoelectric composites that can be printed on fabrics or flexible substrates. The materials are flexible and are processed at lower temperature (130°C). One main PZT particle size (2µm) was mixed separately with smaller piezoelectric particles (0.1, 0.3 and 0.8µm) with different weight ratios to investigate the piezoelectric property d_{33} . The blended PZT powder was then mixed with 40% polymer binder and printed on Alumina substrates. The applied poling field, temperature and time were 8MV/m, 160°C and 10min, respectively. The optimum material gives a d_{33} of 36pC/N with particle sizes of 2µm and 0.8µm and mixed percentages of 82% and 18%, respectively. A screen-printed piezoelectric shoe-insoles (PSI) has been developed as a self-powered force mapping sensor. The PSI was simulated, fabricated and tested. ANSYS results show that one element of PSI sole can produce an open-circuit voltage of 3V when a human of average weight of 70kg makes a gait strike. Experimental results show that one element produced 2V which is less than the simulated results because of the reduction of poling field for the practical device.

1. Introduction

Exploiting ambient resources to power electronic systems using energy converters can save money (i.e. changing the battery) and time. Converting kinetic energy (i.e. vibration or moving body) into electricity is one of the techniques that can power such systems. Piezoelectric materials are one of the methods used for kinetic energy harvesters.

Screen-printing piezoelectric materials is well-suited to the mass production of the proposed devices since it is a straightforward fabrication process. High temperature screen-printed piezoelectric materials have been used in kinetic energy harvesting [1]. This paper presents the development of low temperature printable materials printed on flexible substrates and fabrics. Other work on low temperature materials have concentrated on improving the piezoelectric coefficient d_{33} of the material but have not considered the mechanical flexibility [2-4]. Our previous work [5] showed a study of both piezoelectric properties and flexibility and the optimum material, ECS-PolyPZT produced a d_{33} of 27 pC/N. Improving the piezoelectric properties can be achieved by densifying the film using smaller particles from the same piezoelectric material (i.e. PZT). Finding the optimum particle size and weight percentages is necessary for a maximum film density.

Many papers have reported [6-8] shoe-based energy harvesting but they often require complex fabrication process. The motivation of this work is to develop an improved version of ECS-PolyPZT that can be screen-printed onto flexible substrates (especially fabric-based ones) and exploit its



promising piezoelectric and mechanical properties in piezoelectric shoe-insoles energy harvesters. The screen-printed materials have to be flexible, processed at low temperature (100-200°C) and exhibit a maximum d_{33} .

2. Improved Piezoelectric Composites

2.1. Formulations and Testing Devices

The proposed materials are mixtures of PZT ceramic powder (Pz29, Ferroperm Piezoceramics) mixed with polymer materials. The powder was supplied with only one particle size 2 μ m. Then, it was milled (i.e. using attritor mill) into three sizes (0.15, 0.3 and 0.8 μ m) particles which were used as the filler particles. In the experiment, the 2 μ m particle powder was mixed with single filler separately (e.g. 2 μ m PZT powder was just mixed with 0.8 μ m PZT powder). The blended PZT powder was then mixed with the polymer binder with a 60% overall powder by weight. Table 1 shows the formulations investigated of ECS-PolyPZT inks. The materials were printed in a capacitive structure (CS) on Alumina substrates to test the piezoelectric coefficient d_{33} of the material.

Table 1. ECS-PolyPZT (with 60% PZT) composites investigating formulations.

Particle Size (μ m)	Formulation Ref. #	Large Particle Percentage (%)
0.8	08-1	90
	08-2	82
	08-3	75
	08-4	62
0.3	03-1	98.6
None	02-1	100
0.15	015-1	90
	015-2	82
	015-3	75
	015-3	62

2.2. Poling the devices and d_{33} Measurements

These CS devices were poled with optimum poling conditions used in [5] (Electric field ~10MV/M, poling temperature = 160 °C and poling time = 10 min). Five devices were poled for each formulation. The d_{33} measurements was taken using a PM35 piezometer from PiezoTest. The piezoelectric activity was investigated taking 5 measurements of the d_{33} for each of the 5 samples of each formulation. This gives 25 measurements for each formulation. Figure 1 shows formulation 08-2 provided a d_{33} of 36 pC/N. This is a 25% increase in activity compared to our previous material and is 10% better than PVDF which is a commonly used flexible polymer piezoelectric material. The average d_{33} value for a formulation without fillers is 29 pC/N. The formulations with 0.3 and 0.15 μ m filler particles gave lower d_{33} values.

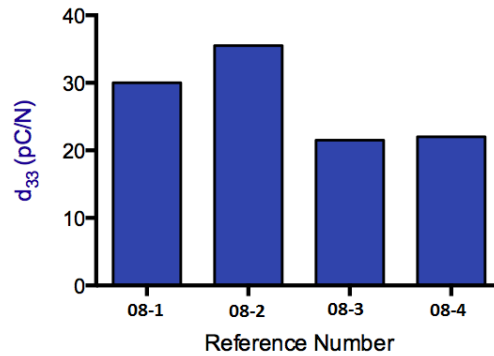


Figure 1. d_{33} values for materials with 0.8µm filler

3. Piezoelectric Shoe-Insole PSI

3.1. Design of PSI

The PSI was designed as shown in figure 2. The PSI consists of two parts, the sole and heel. These parts are considered to be the stress-active parts of the insoles [9]. Therefore, the CS was printed at these locations which reduces the materials used and therefore the overall cost of the PSI device. During walking or running, the heel and sole parts of the insoles are subjected to two types of forces, compressive and bending forces.

Only compressive force is applied to the heel part. However, both compressive and bending forces are subjected to the sole part. At the sole, the device can be used as force-mapping sensor. The sensor can measure the contact force and pressure between the foot and the shoe insole. The sensor is also self-powered by the PSI itself. The sole was divided into 8 elements that sense the force at different locations at the sole part. The number of elements was limited by the number of tracks which increases the non-exploited piezoelectric areas by the top electrode.

Four layers were printed onto these two locations of the PSI as shown in figure 2. The first one is the interface layer which makes the surface of the insole smooth and protects the CS. Then, the CS layers were printed after the interface layer, which are the bottom electrode, piezoelectric material (ECS-PolyPZT) and the top electrode.

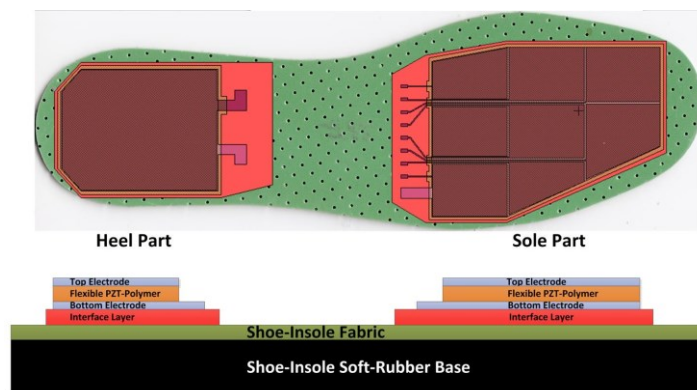


Figure 2. Schematic of top (top) and cross sectional (bottom) views of PSI

3.2. Fabrication of the Device

Screen-printing technique was used to fabricate the PSI device shown in figure 2. The complete printed PSI is shown in figures 3 and 4. Two types of interface layers were used lamination sheets and UV cured, screen-printed Polyurethane UoS-IF#4 supplied by Smart Fabric Inks Ltd [10]. The curing conditions depended upon the polymer. The thermally cured materials were placed in a box oven. The bottom and top electrodes (ELX30) were cured at 125°C for 10min. However, the piezoelectric material ECS-PolyPZT was cured at 130°C for 10min. The average thickness of the printed piezoelectric material is 170µm.



Figure 3. Top view of the printed PSI showing elements 1 and 2



Figure 4. Showing the flexibility of the device

3.3. ANSYS APDL Simulation

The ANSYS results in figure 5 show the output of the sole part of the insole which demonstrates that the PSI can give an open-circuit voltage of 3V when a force strike of average weight of a man 70kg was applied just on element number 1 shown in figure 3 during walking.

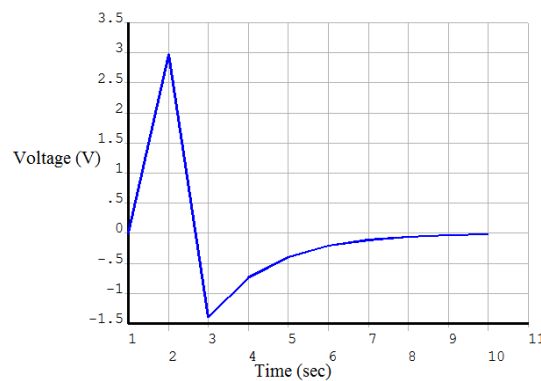


Figure 5. The open-circuit output voltage for one strike for one element of the sole part

3.4. Testing Practical PSI

Testing the practical PSI involved measuring the open-circuit voltage at the sole part of the insole. Typically this material is poled with an applied field of 8MV/m. However, in this case the maximum field was around 4 MV/m as short-circuiting occurred beyond this voltage. The results in figure 6 show that an open-circuit-voltage for one element of the sole part of around 2V. This is less than the simulated voltage because the reduced poling field lowers the piezoelectric properties of the film. This can be solved by increasing the thickness of the piezoelectric material to avoid-short circuiting for later devices. Also, it was found that connecting the sole part elements in parallel can cause the output voltage to change depending upon the magnitude of the applied pressure on each element.

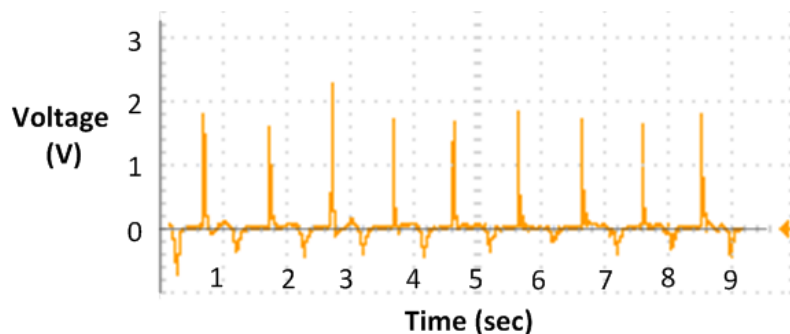


Figure 6. The open-circuit output voltage of one element of normal gait 1strik/sec

4. Conclusion

It was found by varying the filler particle size and particle weight ratios, the d_{33} can be increased. The piezoelectric property d_{33} of a screen-printed flexible piezoelectric composite ECS-PolyPZT were improved to reach 36 pC/N. Also, a new piezoelectric shoe-insole (PSI) was investigated. The sole part of the insole was divided into 8 elements; each element can provide a 2V open-circuit voltage. It was found connecting these elements in parallel will lead to a change in the output voltage due to the different pressure applied to each element.

5. Acknowledgment

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