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Printing of Soft Stretch Sensor from Carbon Black Composites †

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Abstract: Demand for highly stretchable mechanical sensors for use in the fields of soft robotics and wearable sensors has been constantly rising. Carbon based materials as piezo-resistive material are low-cost and have been widely used. In this paper instead of using the controversial carbon-nanotubes, carbon black nano-particles mixed with Ecoflex® as piezo-resistive nanocomposite are used and measure strain up to 100%. Two fabrication techniques incorporating the printing (namely-"layer-upon-layer" and "embedded") of the carbon black nanocomposite will be explored and the performances of the sensors made from these techniques will be evaluated.

Keywords: strain sensor; carbon nanoparticle composites; printing; piezoresistive

1. Introduction

Wearable devices need to be flexible and stretchable to adapt to the users' movements. For instance, a stretchable sensor can provide vital information on the angular orientation of the joints, can be used for gait rehabilitation of stroke patient. The use of traditional metallic and semiconducting techniques have been previously demonstrated [1,2], but has limited potential due to the amount of strain that the device can undergo before yielding, which in some areas might be well beyond the traditional strain sensor's capabilities. Most strain sensors operate based on some change in electrical parameters such as capacitance or resistance [3,4]. Piezoresistive sensors can be fabricated as a thin size, single layer using simpler external electronics than capacitive sensors. Recently, there are reports on piezoresistive sensors with high flexibility, stretchability and reasonable sensitivity [5,6].

Different fabrication processes such as mold based, low temperature chemical vapor deposition, 3D printing, and soft lithography are used to make desirable sensor. Nevertheless, each has its limitations such as high cost, poor durability, limited extensibility, lack of manufacturing scalability [7], etc. However, printing technique is capable of fabricating almost arbitrary geometry. A printing technique with a mixture of carbon-nanotubes (CNT) and Ecoflex® was developed [6] to produce flexible traces embedded in a flexible and highly stretchable Ecoflex® and allow strain measurement up to 300% [6]. The use of CNT based composites [6] is controversial as the use of CNT can be carcinogenic [8]. It was claimed that exposure to low concentrations of CNTs might be harmful. A stretch sensor has high working strains but over time could crack exposing the CNT fibers, which may adhere to the airway epithelial cell of human, increasing the carcinogenic hazard. To eliminate the use of CNT, carbon-black (CB) nano-particles mixed into Ecoflex® (CB-Ecoflex® nanocomposite) as a nanocomposite will be used. CB has reasonable conductivity and sensors based on this material has shown great flexibility, stretchability, repeatability and low cost [9]. In this paper, two fabrication techniques incorporating printing of the nanocomposite will be explored and their performances will be evaluated.

2. Materials and Methods

The commercially available Ecoflex® 00-30 (is mixed 1part A:1part B by weight) was used as elastomer medium which was mixed by CB with particle size of 50 nm (Fuelcell Store (Vulcan® XC72R)) to make CB-Ecoflex® nanocomposite as conductive phase. The CB:Ecoflex® ratio by weight of 1:5 is used. A 1 mL of silicon oil (purchased from Wacker Chemie AG) was added to 10 ml of CB-Ecoflex® nanocomposite to reduce the viscosity so that the CB-Ecoflex® nanocomposite can be extruded through the nozzles. The mixture was homogenized and degassed using Kurabo planetary centrifuge mixer (Mazerustar KK-50S). This Ecoflex® 00-30 elastomer with ability to stretch up to 900% was also used as the sensor's substrate. The use of silicone based elastomer for the conductive phase and substrate increase the stretchability of the sensor.

Strain sensors were fabricated by printing CB-Ecoflex® nanocomposite on partially cured (namely "embedded") and cured (namely "layer-upon-layer") silicone based elastomer substrate. These two fabrication techniques are shown in Figure 1.

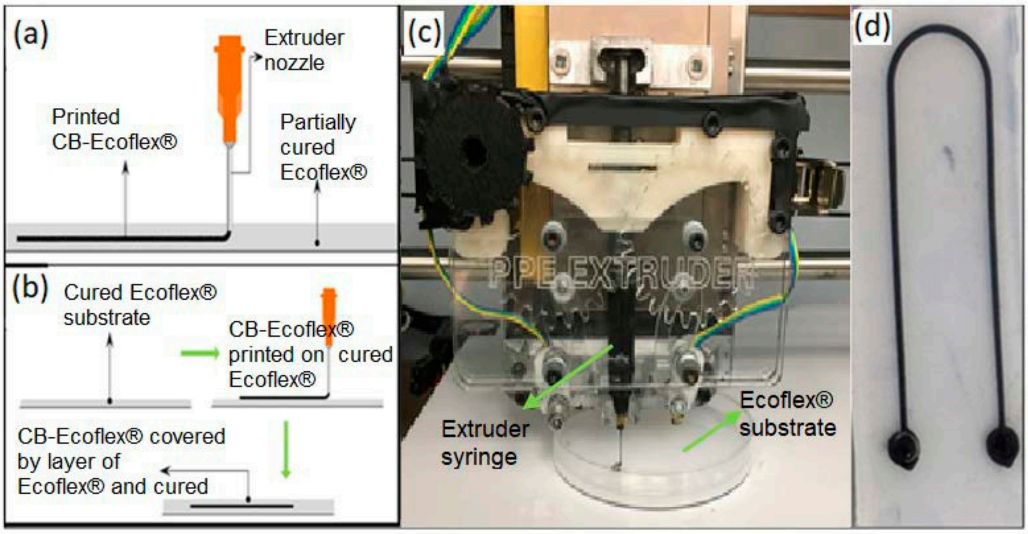

Figure 1. (**a**) A DIY extrusion printer used to print the CB nanocomposite and the fabrication techniques using, (**b**) "embedded" printing, (**c**) "layer-upon-layer" printing and (**d**) a photograph of a printed sensor.

In embedded technique, CB-Ecoflex® nanocomposite was printed on partially cured elastomer substrate and nanocomposite will sink into partially cured substrate due to its weight. The substrate should be able to hold the extruded nanocomposite during printing and the printer nozzle should be able to move in the substrate. For this purpose, printing was started 40 min after the two part Ecoflex® mixture was mixed. In layer-upon-layer technique, CB-Ecoflex® nanocomposite was printed on cured elastomer substrate which was cured for 4 hours after mixing two parts Ecoflex® at room temperature. Second layer of Ecoflex® was poured over to cover the printed CB-Ecoflex® nanocomposite and cured at room temperature for both methods.

3. Results

Change of resistance versus strain testing and SEM were carried out on prepared strain sensors to determine the effect of different technique on the performance of sensors.

3.1. Strain Monitoring

Resistance change with strain testing was characterised by measuring the resistance change of sensor under applied strain up to 100% over 5 cycles of stretching and relaxing. The change in resistance was measured by a Keithley DMM-7510 precision multimeter. The corresponding normalized change of resistance (ΔR/R) versus strain for different sensors are shown in Figure 2 and is clear that the "layer-upon-layer" printing has low reproducibility with different sensors exhibiting different gradients. The gauge factor varies widely from 0.26 to 5.30 (Figure 2a) due to the different gradients for layer-upon-layer printed samples. But the gauge factors only varies slightly from 2.85 to 3.32 (Figure 2b) were obtained for embedded printed samples.

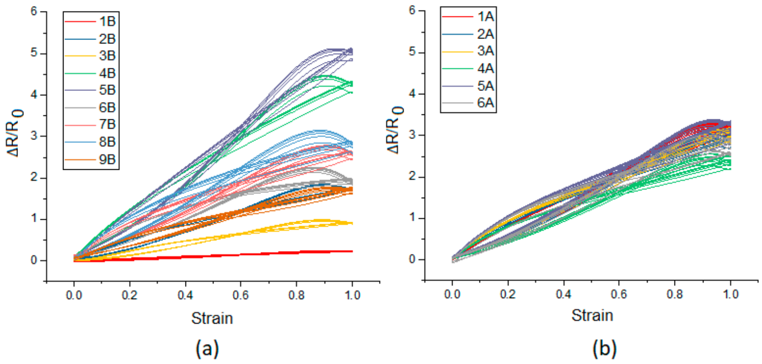

Figure 2. Plots showing the relationship of the change in resistance (ΔR/R) with strain for different sensors fabricated with (**a**) "layer-upon-layer" and (**b**) "embedded" printing, over 5 repeated stretch cycles.

3.2. SEM Micrographs

Figure 3 shows the SEM micrographs of the CB nanocomposites in sensors fabricated with "embedded" and "layer-upon-layer" printing. The SEM micrographs show a clear distinct difference between those fabricated with "embedded" printing (Figure 3a,c) and those from "layer-upon- layer" printing (Figure 3b,d) based on thickness and shape. The thickness of CB-Ecoflex® nanocomposite in "layer-upon-layer" printed (0.55 mm) is significantly less than "embedded" printed (0.95 mm), although they are printed with the same nozzle size.

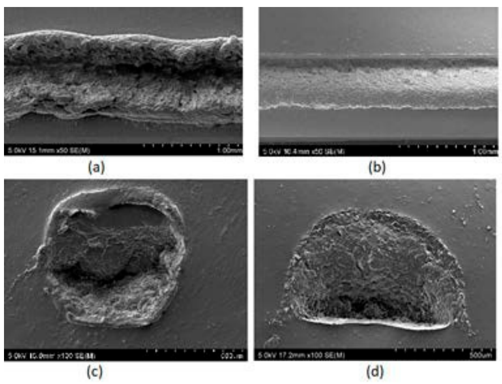

Figure 3. SEM micrograph of the CB nanocomposite in sensor fabricated (**a**) lengthwise cross section of "embedded" printing and (**b**) lengthwise cross section of "layer-upon-layer" printing (**c**) widthwise cross section of "embedded" printing and (**d**) widthwise cross section of "layer-upon-layer" printing.

4. Discussion

The experimental results shows that as the strain increases, the resistance decrease. This is attributed to the increase of inter-particle distances of CB nano-particles within the elastomer medium which is happened for both "embedded" and "layer-upon-layer" printed samples. In the assessment of the difference between two printing methods, it is clear that the "layer-upon-layer" printing has low reproducibility because of inconstant resistance versus strain and could be related to weak interface between CB-Ecoflex® nanocomposite and cured Ecoflex® substrate. Further, the "embedded" printed samples show less hysteresis behaviour compare to "layer-upon-layer" printed samples due to more consistent interface adhesion between the CB-Ecoflex® nanocomposite and partially cured Ecoflex®.

The CB-Ecoflex® nanocomposite layer is thicker for "embedded" printing as it freely sinks into the partially cured Ecoflex®, allowing it to be fully enclosed by partially cured Ecoflex®, compared to layer of CB-Ecoflex® nanocomposite printed layer-upon-layer that was sandwiched and compressed between the cured Ecoflex® layers. As the B-Ecoflex® nanocomposite layer was squeezed between the Ecoflex® layers in "layer-upon-layer" printing, its shape deviated from a circular profile as in embedded printing.

References

1. Jia, Y.; Do, C.D.; Zou, X.; Seshia, A.A. A hybrid vibration powered microelectromechanical strain gauge. *IEEE Sens. J.* **2016**, *16*, 235–241.
2. Do, C.D.; Erbes, A.; Yan, J.; Soga, K.; Seshia, A.A. Vacuum packaged low-power resonant MEMS strain sensor. *J. Microelectromech. Syst.* **2016**, *25*, 851–858
3. Ma, Y.; Liu, N.; Li, L.; Hu, X.; Zou, Z.; Wang, J.; Luo, S.; Gao, Y. A highly flexible and sensitive piezoresistive sensor based on MXene with greatly changed interlayer distances. *Nat. Commun.* **2017**, *8*, 1207.
4. Kenry; Yeo, J.C.; Lim, C.T. Emerging flexible and wearable physical sensing platforms for healthcare and biomedical applications. *Microsyst. Nanoeng.* **2016**, *2*, 16043.
5. Song, Y.; Chen, H.; Su, Z.; Chen, X.; Miao, L.; Zhang, J.; Cheng, X.; Zhang, H. Highly Compressible Integrated Supercapacitor–Piezoresistance-Sensor System with CNT–PDMS Sponge for Health Monitoring. *Small* **2017**, *13*, 1702091.
6. Giffney, T.; Bejanin, E.; Kurian, A.S.; Travas-Sejdic, J.; Aw, K. Highly stretchable printed strain sensors using multi-walled carbon nanotube/silicone rubber composites. *Sens. Actuators A Phys.* **2017**, *259*, 44–49.
7. Muth, J.T.; Vogt, D.M.; Truby, R.L.; Mengüç, Y.; Kolesky, D.B.; Wood, R.J.; Lewis, J.A. Embedded 3D Printing of Strain Sensors within Highly Stretchable Elastomers. *Adv. Mater.* **2014**, *26*, 6307–6312, doi:10.1002/adma.201400334.
8. Liu, Y.; Zhao, Y.; Sun, B.; Chen, C. Understanding the toxicity of carbon nanotubes. *Acc. Chem. Res.* **2012**, *46*, 702–713.
9. Guo, F.; Cui, X.; Wang, K.; Wei, J. Stretchable and compressible strain sensors based on carbon nanotube meshes. *Nanoscale* **2016**, *8*, 19352–19358.