Additive Manufacturing 20 (2018) 119–125

Contents lists available at ScienceDirect

Additive Manufacturing

journal homepage: www.elsevier.com/locate/addma

Full Length Article

Printed Wheatstone bridge with embedded polymer based piezoresistive sensors for strain sensing applications

H.F. Castro[a], V. Correia[a,b], N. Pereira[a], P. Costab[c], J. Oliveiraa[b], S. Lanceros-Méndez[c,d,*]

[a] Algoritmi Research Center, University of Minho, 4800-058 Guimarães, Portugal
[b] Department/Center of Physics, University of Minho, 4710-057 Braga, Portugal
[c] Basque Center for Materials, Applications and Nanostructures (BCMaterials), Parque Tecnológico de Bizkaia, 48160 Derio, Spain
[d] IKERBASQUE, Basque Foundation for Science, 48013 Bilbao, Spain

ARTICLE INFO

Keywords:
Signal acquisition
Wheatstone bridge
Printed electronics
Screen-printing

ABSTRACT

Printed sensors find an increasing interest essentially due to their characteristics of flexibility and low cost per unit area. In this work a screen printed Wheatstone bridge is presented, suitable for strain sensing applications. A piezoresistive ink composite based on biocompatible thermoplastic elastomer styrene-ethylene/butylene-styrene (SEBS) as matrix and multi-walled carbon nanotubes (MWCNT) as nanofillers was used as a piezoresistive sensing material. Different deposition techniques, such as, screen printing, spray painting and drop casting were evaluated in order to optimize the resistance variation related to the piezoresistive effect. Several Wheatstone bridges with one and two sensors were designed to obtain an output sensitivity as a function of the strain submitted to the sensors. Further, different sensor geometries were evaluated to maximize the strain output sensitivity. Electro-mechanical bending tests showed a good linearity and a sensitivity up to 18 mV/V in the all screen printed half Wheatstone bridge output with two MWCNT/SEBS sensors.

1. Introduction

Printed electronics is proven to be a suitable technology for large area and flexible applications due to its low-cost manufacturing and to enable cost-effective ways to implement smart and functional materials at temperatures compatible with polymer substrates. Thus, printed electronics is particularly suitable for application needs characterized by a conjugation of low-cost processes and large-area, i.e. applications that require low-cost per surface area, such as wearable electronics [1,2], interactive surfaces [3] and artificial skin [4], among others.

Sensors are increasingly applied in the determination of multiple physical and chemical quantities in a wide variety of applications in industry, medicine and engineering. Despite their robust features, conventional sensors shows some cost and scalability limitations, as well as difficulties to be embedded in material structures [5].

Flexible sensors are continuously gaining applicability and interest, together with the large area capability, based on a wide range of flexible substrates and innovative materials [6,7] providing scalability and integration solutions otherwise difficult for conventional sensors.

Being the stress/strain sensors, among the most widely used ones due to their wide applicability, new solutions are increasingly explored for flexible applications, to improve integration, and implementation in large areas, highlighting the investigations and solutions related to the fabrication of sensors by additive manufacturing and, in particular, by printing technologies [6–8].

In this scope, this work is devoted to the development of a printed signal acquisition circuit based on the Wheatstone bridge with embedded piezoresistive sensors, which can be applied in touch and interactive applications. Thus, it is possible to obtain an fully embedded circuit that incorporates the sensor, enabling an all-printed on-site solution consisting of sensors, signal acquisition circuit and filtering [9], minimizing the signal degradation by means of electromagnetic noise due to circuit-sensor delocalization.

Several piezoresistive sensor configurations are presented using all screen printed electrodes in a Wheatstone bridge configuration of one and two sensors. The Wheatstone bridge tracks and sensor electrodes were screen printed and the strain piezoresistive material was deposited through different techniques, including screen printing, spray painting and drop casting, in one or two sensors configuration and with different sensor channel geometries.

* Corresponding author at: Basque Center for Materials, Applications and Nanostructures (BCMaterials), Parque Tecnológico de Bizkaia, 48160 Derio, Spain.
E-mail address: senentxu.lanceros@bcmaterials.net (S. Lanceros-Méndez).

https://doi.org/10.1016/j.addma.2018.01.004
Received 12 March 2017; Received in revised form 26 December 2017; Accepted 22 January 2018
2214-8604/

2. Experimental

2.1. Materials and printing methods

The conducting material for the conductive tracks and finger electrodes, silver nanoparticle ink Metalon® HPS-021LV from Novacentrix [10], was screen printed using a polyester screen mesh size of 158 × 158 threads per square inch, with gaps of 64 µm. The squeegee orientation angle was set to 45° relative to the printing substrate and the tension on the mesh was 20 N. The mesh was placed at a 100 µm distance of the substrate. After the printing of the electrodes, the layer was heated at 120 °C for 30 min in an oven (Binder, ED23) under atmospheric environment to sinter the silver particles and remove organic residues.

For the deposition of the strain sensible material, a piezoresistive ink composite based on the biocompatible thermoplastic elastomer Calprene CH-6120, a SEBS copolymer with a ratio of Ethylene-Butylene/Styrene of 68/32 supplied by Dynasol. Multiwall carbon nanotubes, MWCNT, were supplied by Nanocyl: reference NC7000, purity of 90%, length of 1.5 µm and outer mean diameter of 9.5 nm. This composite exhibits excellent mechanical and piezoresistive properties from a wide range of deformations, featuring suitable piezoresistive response up to 80% deformation with a piezoresistive sensitivity near 2.7 [11]. A composite MWCNT/SEBS composite with 5 wt percent (wt %) MWCNT content was prepared by dispersing the MWCNT in cyclopentyl methyl ether (CPME, supplied from Carlo Erba with a density of 0.86 g/cm3 at 20 °C) within an ultrasound bath, and further adding SEBS, as reported by Gonçalves et al. [11], with properly adjusted inks viscosity for the different deposition techniques.

The MWCNT/SEBS piezoresistive ink was deposited on top of the silver screen printed electrodes by screen printing, spray painting and drop casting with viscosities around 2000 cps, 200 cps and 1500 cps, using a polymer/solvent (SEBS/CPME) ratio of 1:6 (g:mL), 1:8 and 1:5 for screen, spray and drop casting, respectively. The screen-printed mesh for the piezoresistive layer deposition was the same used for the printing of the conductive tracks and sensor electrodes. The obtained screen printed films shows an average thickness of 30 µm.The spray technique was achieved with a commercial airbrush from VEKIT DUO, serie APOLO 0.35. To obtain printed films with 3 µm the used pressure was between 2 and 4 bar and using an 80–100 mm distance between pistol and substrate. The films deposited by drop casting (doctor blade coating) shows an average thickness of around 50 µm. After the addition of the MWCNT/SEBS ink through the several deposition techniques, the piezoresistive layer was cured for 60 min under ambient conditions (relative humidity of 35 ± 3%; room temperature 20 ± 3 °C).

The silver nanoparticles conductive tracks and finger electrode configuration were screen printed on a, PET substrate MELINEX® ST-MX505-0100 from DuPont Teijin Films with a thickness of 100 µm, optically clear and printable in both sides. This substrate is pretreated on both sides for improved adhesion of the printed materials and heat stabilized for improved dimensional stability [12].

The morphological cross-sectional images of the sensors were obtained by scanning electron microscopy (SEM) with a Nova NanoSEMTM from FEI equipment.

2.2. Wheatstone bridge

An electrical circuit consisting of a Wheatstone bridge was used to obtain an output signal (VG), in volts, proportional to the resistance variation of the sensors. Fig. 1a and b shows the electrical circuit of the Wheatstone bridge with one and two sensors used in the present work. Fig. 1c and d shows the printed result with R2 and R2, R3 as the piezoresistive strain sensors for the one and two sensors geometry, respectively. Interdigitated conductive layer layouts of the strain sensors were designed with different channel length (L) and width (W), in order to maximize channel width over length (W/L) ratio across the piezoresistive sensor area of 1 cm2. The finger conductive width (df) was also adjusted accordingly. Fig. 1e illustrates the three different screen printed conductive layer layouts of the piezoresistive sensor used in this work, namely: i) L = 0.5 mm and W/L = 170; ii) L = 0.7 mm and W/L = 80; and iii) L = 1.0 mm and W/L = 40.

In order to obtain a resistance in the same order of the piezoresistive sensors, all other resistors in the Wheatstone bridge were built in the same way, but outside of the designated deformation sensing area.

2.3. Electrical characterization

The electrical characterization of the piezoresistive sensor elements was realized by measuring the resistance at room temperature for the different deposition techniques and sensor geometries. The measurement of the electrical resistance was performed with a QuadTech 1920 Precision LCR Meter. For the measuring of the sensor electrical resistance, 20 samples for each different channel W/L ratio and deposition technique were used, so that the reproducibility of the printing materials and methods was assured. For the electrical characterization of the Wheatstone bridge, a Keithley 2400 SourceMeter was used to apply a bias voltage of 5 V to the source voltage (VS) and to measure the output voltage VG. For the Wheatstone bridge characterization, 5 samples were used for each different channel W/L ratio and deposition technique. The temperature sweeps between 20 °C and 90 °C were performed in 10 °C steps and the output voltage of the Wheatstone bridge, VG, was measured at each step.

2.4. Electro-mechanical characterization

For the sensitivity to deformation of the printed Wheatstone bridge, electro-mechanical bending tests were performed. The VG is measured using Agilent 34401A Digital Multimeter when applied a bias voltage of 5 V to VS, at the same time that the sensor is submitted to mechanical stress. Unless otherwise stated, all VG measurements are showed subtracted of the bias voltage resulting of the unbalance condition due to differences in the resistances of the Wheatstone bridge elements. All output sensitivity measurements related to deformations are identified by ΔVG and calculated from Eq. (1):

$$\Delta V_G = V_G|_{Z=2.5mm} - V_G|_{Z=0mm}, \quad (1)$$

where $V_{G|=\ 2.5mm}$ is the output voltage when the sensors are in bended state with Z = 2.05 mm, and $V_{G|}= {}_{0mm}$is the output voltage in the resting state with Z = 0 mm.

For the electro-mechanical characterization of the Wheatstone bridge, a sensing area was designated both for the one and two piezoresistive strain sensors geometry. Fig. 2a illustrates the adopted sensing area. All electro-mechanical characterization experiments were performed using a three-point bending mechanical mode with a universal testing machine Shimadzu-AG-IS. Fig. 2b and c illustrates the used three-point bending mechanical mode, were two fixed points are located in the extremities of the piezoresistive sensor, while the third point is located in the middle of the sensor and a vertical displacement (Z) is applied in relation to the two extremity points. The electro-mechanical tests consisted in several loading-unloading cycles with Z ranging between 0 mm and 2.05 mm, while recording the VG.

3. Results and discussion

Fig. 3 shows optical images of the printed sensors with a channel geometry of W/L = 170. Fig. 3a displays the screen printed sensor electrodes without the deposition of the piezoresistive ink. From this picture it can be observed that it is possible to obtain a fine screen printed pattern of Ag electrodes, with the selected screen mesh properties, allowing to obtain L and df down to 0.5 mm. On the other hand, Fig. 3b, c and d shows the same sensor structure, as depicted in Fig. 3a,