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Using electrofluidic devices as hyper-elastic strain sensors: Experimental and theoretical analysis

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ABSTRACT

The use of hyper-elastic polymers for the development of oft sensors with large deformation capabilities is described here. Using soft silicone elastomer (Ecoflex 00-50) and liquid metal alloy (Galinstan), we present the characterization of an electrofluidic strain sensor. The originality of such sensor lies in the capability to resist to large deformation (higher than 200% cycled 150 times). Several device designs have been investigated to enhance the electrical response of the sensor as a function of its elongation. We discuss here the results of cyclic deformation and strain on the sensor. We also present a theoretical study based on a numerical simulation performed with COMSOL Multi-Physics and an analytical model of the sensor's response to elongation. Numerical simulations were done based on the Mooney–Rivlin model for hyper-elastic materials. The analytical calculations were obtained considering the evolution of the sensor resistance according to the variations of the channel's dimensions. The two methods have shown a very good correlation with the experimental results. They offer new possibilities to design and prototype sensors suitable for application involving large deformation such as soft robots or wearable sensors to monitor physiological parameters.

1. Introduction

The integration of strain gauges in miniaturized systems has been developed and optimized for a large range of applications such as robotics, health care monitoring, MEMs, etc. They provide simple, low cost and efficient devices to measure strains associated with material elongation. Most of these sensors are however limited (i) by their rigidity that limits the compliance with microstructured or deformable substrates (e.g. flexible polymers, skin, ...) and (ii) by their rather low deformability to measure stretching higher than 1%. In most of these applications, the material composing the sensor is usually the major limiting factor.

The use of thin layers technologies to produce sensors and connection wires is a way to increase the elongation capabilities of such systems [1–3]. These technologies improve the integration capabilities on flexible substrates and the possibility to develop new monitoring devices but they still require expensive and demanding fabrication processes.

The combination of soft materials with microfluidic technologies offers unique possibilities in terms of flexibility and stretchability. In particular, recent works have shown the potential of soft sensors based on microchannels molded inside elastomers (e.g. PDMS, polydimethylsiloxane) filled with an electrically conductive fluid. Such sensors have a higher capability to extend and thanks to the conductive liquid the electrical connection is not lost during the stretching. Microfluidic prototyping has been used to develop tunable antennas [4–7], wearable electronics to monitor skin deformations on a person [8–11], to develop tactile feedback sensors [12,13] or 3D-strain sensor [14]. However there are still few papers dealing with theoretical analysis or aging properties of such stretchable sensors [15].

We present here the development of a strain sensor based on microchannels molded in a soft hyperelastic elastomer (Ecoflex 00-50 – Smooth-on, Inc.) and filled with a liquid metal alloy (Galinstan–gallium/indium/tin alloy). Samples have been characterized experimentally to investigate their electrical response, ageing and repeatability. In addition we propose a numerical simulation and an analytical model developed to predict sensor's response under strain. We'll show that these theoretical models are in good agreement with experimental data.

2. Materials and methods

The sensor's design is based on the fabrication of microfluidic channels using a hyper-elastic polymer as a base material (Ecoflex 00-50). This bi-component silicone material withstands larger

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deformations than PDMS. It exhibits a Young's modulus around 200 kPa and a maximal stretching ratio before breaking of 980% (0.8–2 GPa and 50% for the PDMS). Microchannels were obtained through a conventional replication process with a metal master mold (brass) obtained by micromilling (Minitech Machinery). Two different channel designs (100 μm high and 200 μm wide) based on serpentine geometries were fabricated as positive (ie protruding) structures on the molds. The first serpentine design has its main axis oriented parallel to the direction of the inlet and outlet while that of the second shape is perpendicular to this direction (Fig. 1f).

The microfluidic devices were fabricated as follows (Fig. 1): the Ecoflex base components were mixed together and poured on the master mold. The uncured elastomer was first degased, then cured under vacuum at room temperature during 4 h and finally removed from the mold.

Both the inlet and the outlet were punched in the molded channel. The device was finally sealed with a 300 μm thick layer of elastomer that was previously spin-coated and cured on a Si wafer (treated with FTDS). Bonding was performed with an oxygen plasma surface treatment (1 min at 100 W) on both surfaces.

An additional oxygen plasma treatment was further performed to bond the sensor's ends on two 76 mm × 26 mm glass slides that were used as holders for stretching experiments. This configuration was chosen to preserve the mechanical rigidity of the electrical connectors' area.

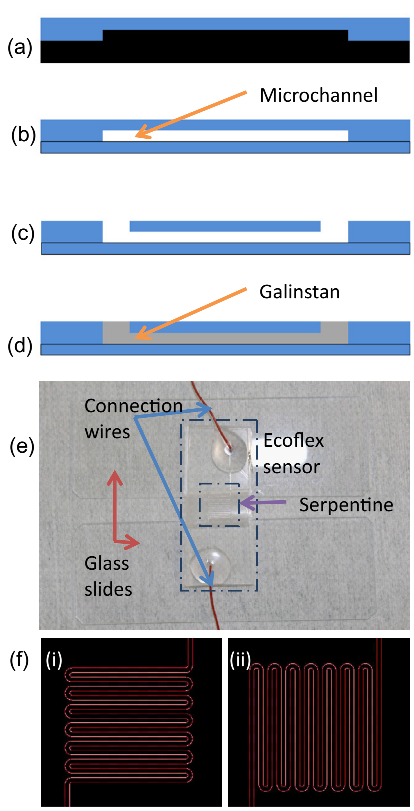

Fig. 1. Sensors' fabrication process. (a) Microchannel molding: Ecoflex prepolymer mixture was poured on a microstructured brass master mold and cured at room temperature (b) Microchannel was sealed using a 300 μm thin Ecoflex membrane through an Oxygen plasma treatment. (c) Inlet and outlet were punched. (d) The microchannel was finally filled with Galinstan liquid metal and then electrodes were connected. (e) Picture of a fully assembled sensor. (f) Layout of the two different serpentine designs: perpendicular (i) or parallel (ii) to the stretching direction.

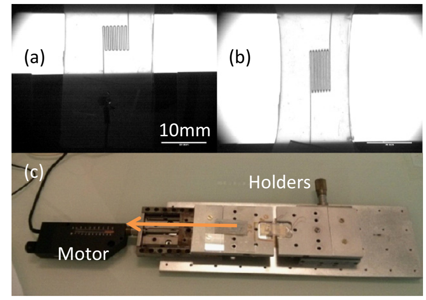

Fig. 2. Pictures of (a) non-deformed sensor, (b) deformed sensor (the scale bars on the pictures represent 10 mm). (c) Picture of the experimental stretching setup based on a linear stage (the orange arrow represents the stretching direction).

To finish the fabrication of the sensor we filled the microchannel with Galinstan and inserted electrically conductive wires (copper, 0.120 mm diameter) in the inlet and outlet to measure the electric resistance. The wires were held in place and the channels sealed by dispensing a drop of Ecoflex at the entrance.

Mechanical characterization of the samples was done by stretching the sample on a homemade automated setup. The glass slides bonded on the sensor are maintained in place by custom made clamps and stretching test was performed using a linear stage (Fig. 2, Newport 850 g driven by a Newport ESP300). For each experiment, the length of the system was incrementally increased (up to 250%) while the electrical resistance of the electrofluidic channel was continuously measured with a Keithley 2000 multimeter. Deformation cycles were also performed in order to investigate the repeatability of the measures and potential ageing of the sensors. In this case the device was periodically stretched with an elongation from 0% to 200% (0–30 mm) with a speed of 0.2 mm/s. The electrical resistance of the device was stored every 510 ms.

3. Theoretical models

3.1. Numerical simulation

Numerical simulations were performed in two steps with COMSOL multiphysics. Using a sequential processing, the model calculates the mechanical deformation due to stretching and then the electrical conductivity of the deformed geometry.

EcoFLex is a hyper-elastic material so that conventional linear elastic models do not describe the behavior of such a material. We implemented a Mooney–Rivlin model where the strain energy density is connected to the deformation tensor F by the following relation:

$$W = C_{01}(\bar{I}_2 - 3) + C_{10}(\bar{I}_1 - 3) + \frac{1}{2}k(J - 1)^2$$

With $J = \det F$ (F is the deformation tensor), $\bar{I}_1$ $\bar{I}_2$ two invariants of the left Cauchy-Green deformation tensor $B = F \cdot F^T$ and C_{01} = 10401,8 Pa and C_{10} = 21362,8 Pa are two empirically determined material constants [15].

Thanks to these values the simulation is able to calculate the deformation of the system. The basic geometry is a bloc of Ecoflex with a rectangular shape (15 mm long, 8 mm width and 1 mm height). A serpentine structure corresponding to the microfluidic channel (200 μm height, 200 μm width and 5 mm long, Fig. 4) was integrated in this block. As an approximation, we considered the serpentine having the same mechanical properties as the EcoFlex bulk material but having additional electrical conductivity (Galinstan: 3.46 × 10^6 S/m). For a given stretching, the numerical model calculates first the mechanical deformation of the system using the Mooney–Rivlin hyper-elastic model and then determines