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Research Article

Polymer-Based Self-Standing Flexible Strain Sensor

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The design and characterization of polymer-based self-standing flexible strain sensors are presented in this work. Properties as lightness and flexibility make them suitable for the measurement of strain in applications related with wearable electronics such as robotics or rehabilitation devices. Several sensors have been fabricated to analyze the influence of size and electrical conductivity on their behavior. Elongation and applied charge were precisely controlled in order to measure different parameters as electrical resistance, gauge factor (GF), hysteresis, and repeatability. The results clearly show the influence of size and electrical conductivity on the gauge factor, but it is also important to point out the necessity of controlling the hysteresis and repeatability of the response for precision-demanding applications.

1. Introduction

Technological advances and the need of new services in applications related to robotics require the development of new resources and materials. These resources and materials must be designed to improve the well-being of people, at the same time insuring their safety. The integration of conventional strain gauges in flexible structures has been difficult because of the existing mechanical restrictions. Nowadays, there is an increasing tendency of developing smart sensors based on polymeric materials capable of cutting down the structural restrictions of conventional sensors [1, 2]. This new generation of light, flexible, and low-cost polymeric sensors are very promising and useful in the field of robotics and wearable electronics. Some approaches in the design of this type of sensors, to be used in the field of people rehabilitation and health monitoring, have already been proposed [3–5]: applications for the measurement of biological signals (electrocardiogram, breathing, joint position and movements, skin temperature, etc.) could be developed through different devices implementation (woven or knitted metal electrodes, EAP-based textile fibers or small-size strips, optical fibers, etc.). This new generation of nanocomposite-based polymeric sensors are flexible and easy to deform, being able to be integrated in such structures without changing their behavior.

Sensors proposed in previous works for strain/stress and pressure measurements were built based on a combination of nanowires and carbon nanotubes on elastomeric materials [6–11]. In these cases, the piezoresistance property of the final composite material is used as the sensing mechanism; thus, changes in the conductivity of the composite material following a linear relationship with strain variations [6]. Carbon nanotubes were the most extensively studied materials in this area, but in spite of the optimal performance observed, the high cost of these nanotubes increased the cost of the sensor technology, making it inappropriate for some large surface applications. Furthermore, these composite materials are deposited on textiles or other supporting bases, where the final flexibility depends on the intrinsic properties of the support used. In this paper, the design of a self-standing, low-cost, and flexible strain sensors, based on composites made using high aspect ratio carbon nanoparticles and elastomeric polymer materials, is presented. The nanocomposite material is a self-standing film not requiring an additional supporting layer, pointing to the nanocomposite as a promising material for further application in wearable electronics.

Table 1: Electrical conductivity (S/cm) versus Dimensions (mm).

Electrical conductivity (mS/cm)	Length (mm)	Width (mm)	Thickness (mm)
0.03–0.07	55	19	0.375–0.4
0.1	55	20	0.25–0.3
0.3-0.4	55	18	0.3–0.325
0.5-0.6	55	19	0.375–0.4
2	55	20	0.35–0.375
5	55	20	0.35–0.4

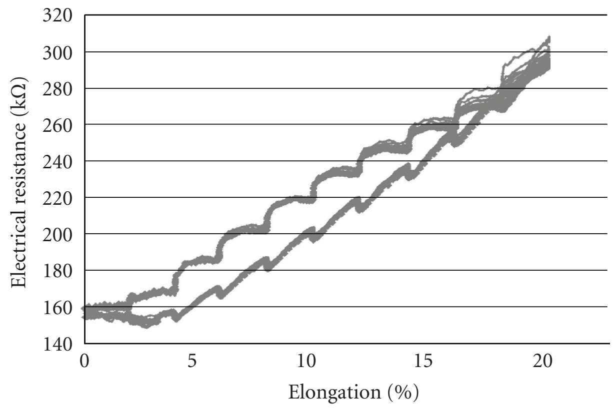

Figure 1: Electrical resistance (KΩ) versus elongation (%) for 0.5 mS/cm electrical conductivity elastomer.

2. Experiment

2.1. Sensitive Composite Materials. Elastosil LR 3162 A/B, from WACKER Ltd., was the selected material as the main component in the production of the sensors. It is a liquid silicone rubber with good mechanical, electrical, ageing, and fast vulcanization properties that make it very attractive for its application in sensors.

It has a density of 1.12 g/cm^3 at 23°C, a viscosity of 6500 Pa·s, a tensile strength of 5.4 N/mm^2, 410% of elongation at break, and a tear strength of 12 N/mm. The material requires 10 minutes at 165°C, under pressure, as cure condition.

The nanofillers were purchased from CheapTubes (USA). High aspect ratio nanofillers were chosen for the preparation of the nanocomposites. The electrical properties of polymeric composites are highly dependent on volume, distribution, size, shape, phase orientation, and interaction with the added nanoconductive fillers. The electric charges create electrical pathways, and there is a transition of the material from electrically insulating to conductive. In order to establish a compromise between desired physical and electrical properties, an appropriate loading level for the conductive fillers is needed. Thus, if the elastomer were highly loaded to reduce the resistivity, the material would become too hard and would exhibit lower elongation and tensile strength. The best approach would be to reach an equilibrium between mechanical and electrical properties of the nanocomposite. In this work, the rubber was filled with a wide range of conductive nanoparticle loads, and different filler contents were tested to obtain the required electrical and mechanical characteristics.

Based on the mixture of Elastosil and carbon nanofillers, different sensors, with a wide variety of electrical conductivities between 0.03 and 5 mS/cm, were built. Nanoparticle fillers content varied between 5 and 10%. Furthermore, different sensor sizes were analyzed. Their electrical conductivity and dimensions are shown in Table 1.

2.2. Sensor Characterization System. The manufactured sensors were characterized through multiple elongation-contraction cycles, using a strain tester. This device was composed of a traction instrument and a data acquisition system. The number, strain change ratio, and elongation of the cycles could be configured dynamically. This automation allowed completing multiple elongation-contraction cycles to characterize the material. Depending on the mechanical properties of the materials to characterize (size, elongation at break, tear strength, etc.), different parameter configurations were tested. Parameters of strain rate (0.001 m/s up to 0.01 m/s) and elongation cycles were chosen, taking into account the real applications where the materials could potentially be used.

3. Results and Discussion

In this section, the results after sensor characterization are shown. For sensor characterization purposes different properties have been studied: dependence of the electrical resistivity with sensors size, elongation and electrical conductivity, gauge factor, hysteresis, linearity, and repeatability. Besides a gauge factor or sensitivity adapted to the application [12, 13], it is necessary to obtain a good linearity, repeatability, and controlled hysteresis in the material response.

3.1. Electrical Resistivity. Sensors with different conductivities were cycled up to 21–27% of elongation. Figure 1 shows the electrical resistance response through multiple elongation-contraction cycles for a sensor with an electrical conductivity between 0.5 and 0.6 mS/cm. As can be observed in the figure, sensor behavior remains constant during the different characterization cycles. The measurements show a sawtooth curve for Figure 1. This form is due to the fact that, after every 2% of elongation, a period of 2 seconds is left in order to achieve the stabilization of the resistance. During this time, the electrical resistance is measured but without changing the elongation value in the sensor. The period of time has to be long enough to allow the total variation of the electrical resistance after the elongation. The sawtooth form is not shown in the following figures because a tendency line has been used as a representation of the measured data.

The elongation of the sensor produces a decrease in the number of electrical connections between the conductive particles in the material, bringing about an increase of the resistance. Figure 2 shows this fact, where, for every sensor,

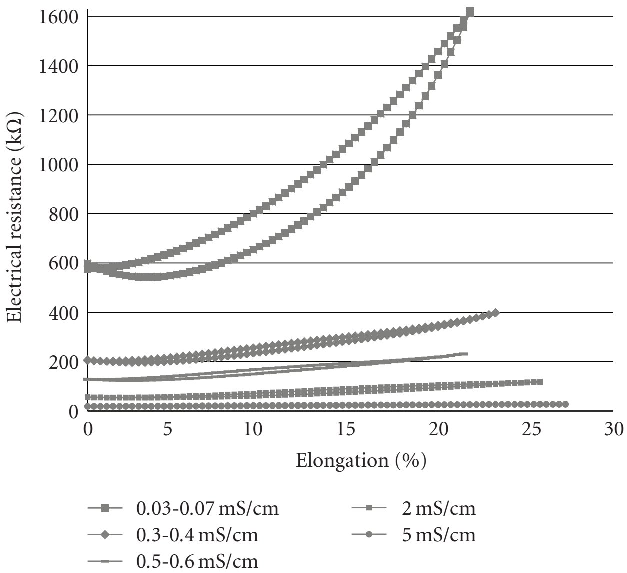

Figure 2: Electrical resistance (KΩ) versus elongation (%) for different electrical conductivity elastomers.

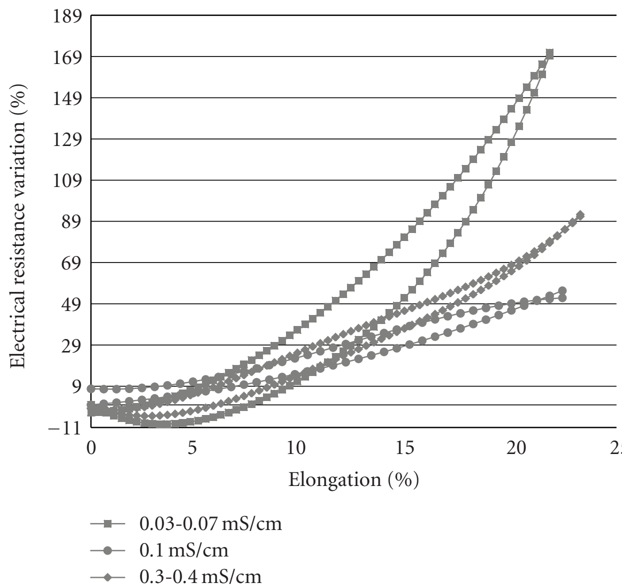

Figure 3: Electrical resistance variation (%) versus elongation (%) for different electrical conductivity elastomers.

the working electrical resistance increases as the elongation increases. Furthermore, for a certain elongation percentage, the absolute increment of electrical resistance is lower for higher electrical conductivity materials. As the volume of conductive fillers in the sensors increases, the electrical conductivity is higher, and the hardness and stiffness of the sensors are also higher. These physical properties are the reason why for the same level of strain the electrical resistance variation is lower as the electrical conductivity of the sensors increases.

The working electrical resistance for undeformed sensors also decreases with the increase of the electrical conductivity. The electrical charges form electroconductive channels, and there is a transition of the material from electrically insulating to conductive. This happens when the conductive fillers concentration in the material is bigger than the critical percolation volume.

The gauge factor is the parameter used to define the sensitivity of the sensor. It measures the ratio of relative change in electrical resistance to the mechanical strain ε, which is the relative change in length, of the undeformed sensor.

As Figures 3 and 4 show, the gauge factor is not directly proportional to the electrical conductivity. The highest value is obtained for the sensor with electrical conductivity between 0.03 and 0.07 mS/cm. On the other hand, the poorest value belongs to the highest electrical conductivity sensor, 5 mS/cm.

The response is not totally linear in any sensor. There are regions, in the relation between the electrical resistance variation and the elongation, where the response is nonlinear. This can be explained as a change in the geometrical structure of the sensors, because of the physical properties of the material, by the effect of the remaining elongation during multiple strain cycles.

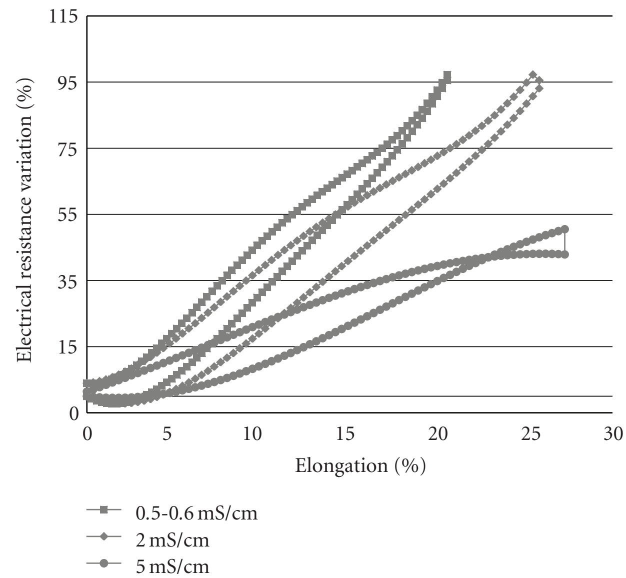

Figure 4: Electrical resistance variation (%) versus elongation (%) for different electrical conductivity elastomers.

So, as it is advisable to have a suitable sensitivity value, with a linear sensor response in the desired working range, it is of great importance to be very careful in the formulation of the sensor material composition.

3.2. Repeatability. Repeatability refers to the capacity of the sensor to provide the same response, for the same input signal, keeping constant the measurement conditions. This property is necessary to ensure the availability of the sensor for a long period of time and the reliability of the obtained

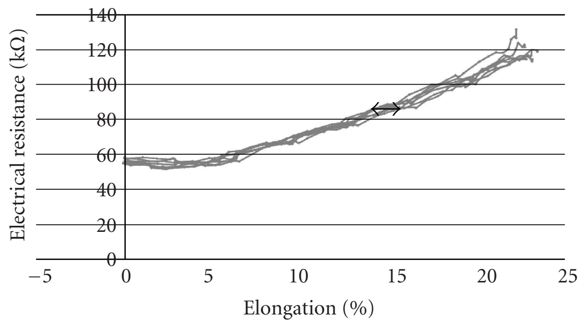

Figure 5: Deviation between measured elongation cycles for 2 mS/cm electrical conductivity elastomer.

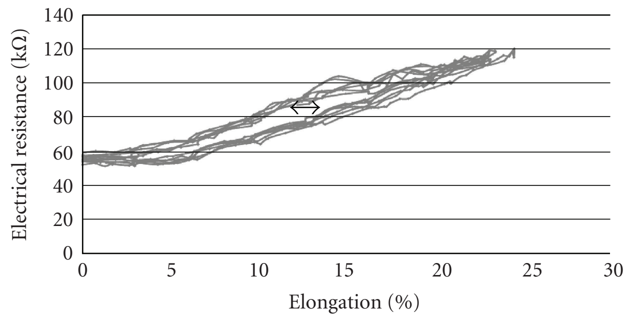

Figure 6: Hysteresis between measured elongation-contraction cycles for 2 mS/cm electrical conductivity elastomer.

Table 2: Deviation (%) versus electrical conductivity (S/cm) and elongation (%).

Electrical conductivity (mS/cm)	Elongation (%)	Deviation (%)
0.1	22	6.56
0.5-0.6	21	2.89
2	26	3.26
5	27	4.5

Table 3: Hysteresis (%) versus electrical conductivity (S/cm) and elongation (%).

Electrical conductivity (mS/cm)	Elongation (%)	Hysteresis (%)
0.1	26	38
0.3-0.4	24	9.5
0.5-0.6	21	10
2	26	14
5	27	20

measures. In this work, the repeatability between different cycles has been measured.

Figure 5 shows the characterization of multiple cycles and the deviation between them, during the elongation process, for a 2 mS/cm electrical conductivity elastomer. The deviation (%) value for each electrical conductivity (mS/cm) sensor and elongation (%) value is presented in Table 2.

The best value obtained is a deviation of 2.89% of the elongation cycle, for an elongation of 21% of the elastomer initial length. This value is obtained for the sensor with electrical conductivity between 0.5 and 0.6 mS/cm. However, this value is close to the deviation value obtained for the sensors of 2 mS/cm of electrical conductivity, but in this case the elongation is higher. For a similar elongation value, 27%, the deviation value for 5 S/cm of electrical conductivity is higher than that for 2 mS/cm of electrical conductivity sensor. The worst deviation value is obtained for the sensor of lower electrical conductivity.

3.3. Hysteresis. Hysteresis comes out in systems where the output does not only depend on the input, but that also depends on the history of the input. In Figure 6, the hysteresis in multiple measured elongation cycles is shown for 2 mS/cm electrical conductivity elastomer. This effect causes the difference between the sensor response during elongation and contraction. The hysteresis (%) value for each electrical conductivity (S/cm) sensor and elongation (%) value is presented in Table 3.

The best value is obtained for the sensors of electrical conductivity between 0.3 and 0.4 mS/cm, 9.5% of maximum hysteresis for an elongation of 24%. This value is close to the hysteresis value of the sensor with electrical conductivity between 0.5 and 0.6 mS/cm. But in this case the elongation is lower, around 21%. The hysteresis value increases as the sensor electrical conductivity changes to 0.1 mS/cm, 2 mS/cm, and 5 mS/cm.

4. Conclusions

The design and characterization of polymer-based flexible-strain sensors have been presented in this paper. The behavior of the sensors, in terms of dimensions and electrical conductivity, has been studied, under multiple elongation-contraction cycles, carried out in a strain tester. A composite material, based on Elastosil reinforced with conductive nanoparticles, was selected due to its properties that make it appropriate to be integrated in flexible structures. Different sensor characteristics have been analyzed; physical characteristics, as electrical conductivity and dimensions, and working characteristics, as gauge factor, linearity, hysteresis, and repeatability. The influence of size, elongation, and electrical conductivity on the sensitivity of the sensor has been demonstrated. A good sensitivity value, adapted to the application, is very important, but it is not less important to have a linear response, a good repeatability, and a low hysteresis factor. It was found that the sensor with the best compromise between sensitivity, repeatability, and hysteresis, was that with an electrical conductivity of 0.3-0.4 mS/cm. From this point on, the performance of the sensors, in terms of repeatability and hysteresis, gets worse with the variation of the electrical conductivity.

Although results are very promising, the next phase would be to measure the behavior of the sensors under different humidity and climatic conditions.

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