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Fabrication and testing of re-entrant auxetic samples and sensor: Numerically and experimentally

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ABSTRACT: Auxetic structures (negative Poisson's ratio) are a group of materials that expand (contract) under tensile (compression) longitudinal loading. In this work, the effect of re-entrant auxetic structure geometry on Poisson's ratio was investigated under large tensile loading experimentally and numerically and showed that the location and stiffness of rotation joints are two new important parameters affecting the value of Poisson's ratio. Poisson's ratio increases as the rotation joints tighten and move away from the center of the structure. Therefore, by changing the location and stiffness of the rotation joints, it will be easy to obtain re-entrant auxetic structures with different Poisson's ratios, which makes it possible to build piezoresistant auxetic sensors with different sensitivities. A highly sensitive, stretchable piezoresistant auxetic sensor made of silicon rubber and chopped carbon fibers is proposed for low strain values. The main feature of this sensor is its high sensitivity for strains less than 6%, which previous works have been unable to detect this range of strains. Shifting strain is the value of strain in which the Poisson's ratio of the structure changes from negative to positive. The provided auxetic sensor performs exceptionally well until the shifting strain and then performs as conventional sensors. This improvement in sensing performance is about 150% (in terms of gauge factor).

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1- Introduction

Poisson's ratio ( ) is defined by dividing the lateral strain to the longitudinal strain in the longitudinal tensile loading [1]. This parameter indicates how material becomes narrow when stretched. In this work, a type of metamaterial with negative Poisson's ratio (auxetic structure) was designed and used as auxetic piezoresistant sensor. There are two methods for designing auxetic structures. The first one is parametric optimization that the desired Poisson's ratio is obtained by changing the dimensions of the structure and the second one is topology optimization approach that the desired Poisson's ratio is achieved by using mathematical rules [1-3].

Piezoresistant pressure sensors convert input force into an electrical signal by changing the resistance. These sensors have attracted considerable attention due to their simplicity of design and ease of use. Most flexible piezoresistant sensors are made by coating a flexible material (including open-cell fibers, films, and foams) by conductive coating of nanomaterials (including carbon nanotubes, graphene, nanowires, and nanoparticles) by using process methods such as mixing, coating, and printing [4-10]. In addition to nanomaterials as active sensing elements, the properties of the base material also play a key role in determining the final sensing performance. Most studies on the effects of the base material have focused on the elastic modulus, and it has been suggested that the porous base material with reduced elastic modulus increases the sensing property. Furthermore, the Poisson's ratio can affect the sensing performance of piezresistant sensors, although not many studies have been performed on it [7].

In this article, the relationship between the deformation behavior of auxetic structures and their sensing properties has been investigated. To design an auxetic piezosensitant sensor, three steps including designing the auxetic structure, investigating the deformation and converting it into an auxetic piezosensitive sensor must be performed which these three steps were explained in this work. To this end, re-entrant auxetic structures were designed by level set topology optimization method and then were printed by 3D printing technique. The deformation behavior of these structures has been investigated under large tension experimentally and numerically and it has been shown that re-entrant auxetic structures are auxetic up to a specific strain, called shifting strain, and then have positive Poisson's ratio. Finally, by using the obtained ideas, production method of a piezoresistant auxetic sensor for small value of strains was discussed.

2- Methodology

The volume fraction and Poisson's ratio of the re-entrant auxetic structure used to manufacture the sensor are 40% and -1.2, respectively. The presented auxetic sensor consists of 36 unit cells and its dimensions are 48x60. In order to find

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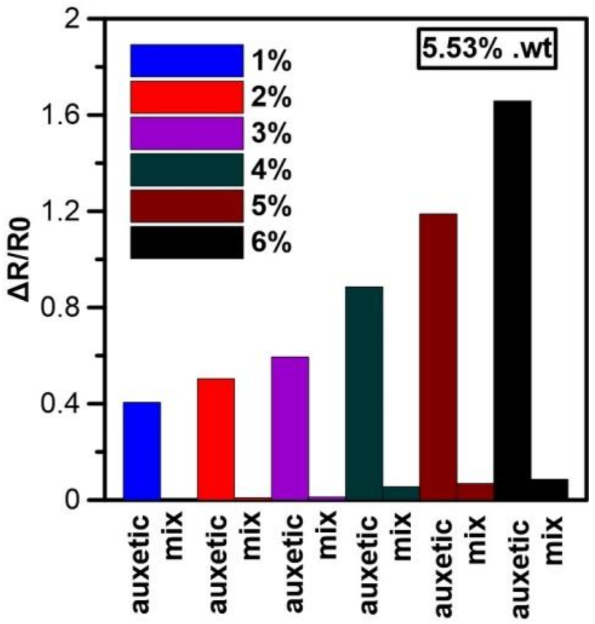

Fig. 1. Comparison of performance of conventional and auxetic sensors made with a mixture of silicone rubber and chopped carbon fibers.

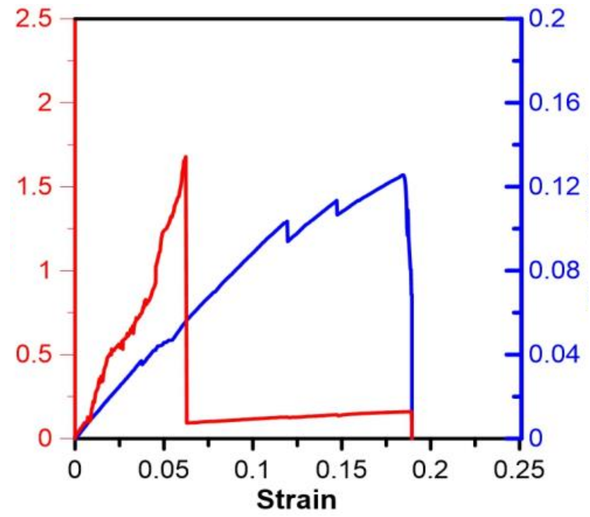

Fig. 2. Electromechanical performance (stress-strain diagram and GF characteristics) of an auxetic sensor

the sensitivity threshold of the auxetic sensor, composites with different volume fractions were made of silicone rubber and chopped carbon fibers with a volume fraction difference of 0.5% (5 samples for each case). The sensitivity threshold was found to be 5.53% of chopped carbon fiber volume fraction.

The mixture of silicone rubber and chopped carbon fiber was molded onto the die of auxetic structure and after one hour the auxetic structure was dried and peeled off from the die. The Victor 86C digital multimeter which has the ability to connect to a computer was used to record the changes in sensor resistance. Simultaneously, the data was saved by using DMM Data software. The clamp jaws of the zwick/Roell z100 universal testing machine were insulated using plastic glue.

3- Results and Discussion

In previous works, the performance of two groups of sensors has been investigated: (a) Combination of chopped carbon fiber and silicone rubber [9] (b) composite sandwich of material of sensor [10]. The first group had a relatively small gauge factor (approximately 50) at the strain of 25% while The composite sensor showed better results including hysteresis (3% at 50% strain), higher sensitivity (100<GF<120) and considerable stretchability (approximately 300%). However, both of them were restricted to large strains and were not able to measure low strains. In this work, an auxetic sensor for measuring low strain values with good performance (lower than 6%) was proposed.

Fig. 1 shows the results of this work with the previous work [9] for different strains from 1% -6% in terms of sensitivity. According to Fig. 1, both previous sensors could not detect strains of less than 4% and for strains in the range of 4% -6%, the sensitivity of the proposed sensor is significantly higher than the previous conventional sensor. Fig. 2 shows the electromechanical performance of the sensor. In this Fig. , the Y-axis on the right shows the mechanical properties of the sensor until failure point. At the strain of 18%, the sensor was disjointed and before the mentioned strain, the diagram was continuously decreasing and increasing due to rupture of structure cells and after the structure was completely broken, the diagram drops sharply. The Y-axis on the left of the diagram simultaneously shows the electrical behavior of the sensor. As explained before, the performance of the sensor is very good until the strain of 6% and after this value of strain, the sensor loses its auxetic properties and behaves like conventional sensors. Before the strain of 6%, the diagram of electrical performance was increased. It is noticeable that after the mentioned strain until the strain of 18%, the diagram was still increasing but the slope of that was reduced.

4- Conclusions

In this work, a high-sensitivity low-strain sensor made of a mixture of silicone rubber and chopped carbon fiber using an auxetic structure is proposed. We have shown that the auxetic sensor has a good performance up to the shifting strain and then their performance is the same as conventional sensors because until the shifting strain the value of Poisson's ratio of structure is negative and then it becomes positive. Significant improvement in the gauge factor and sensitivity of the sensor has been observed. Silicone rubber as a base material and chopped carbon fibers as a conductive element were mixed together and they were molded in the form of a re-entrant auxetic structure. Previous studies could not measure low strains but due to the softness of the silicone rubber and the low value of shifting strain of the structure, strains less than 6% can be measured well with our proposed sensor.

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