Proceedings of the ASME 2018 Conference on Smart Materials, Adaptive Structures and Intelligent Systems
SMASIS2018
September 10-12, 2018, San Antonio, Texas, USA

SMASIS2018-8011

3-D PRINTING OF DIELECTRIC ELECTROACTIVE POLYMER ACTUATORS AND CHARACTERIZATION OF DIELECTRIC FLEXIBLE MATERIALS

David Gonzalez
School of Engineering Technology,
Purdue University
West Lafayette, Indiana, USA

Brittany Newell, PhD
School of Engineering Technology,
Purdue University
West Lafayette, Indiana, USA

Jose Garcia, PhD
School of Engineering Technology,
Purdue University
West Lafayette, Indiana, USA

Lucas Noble
School of Engineering Technology,
Purdue University
West Lafayette, Indiana, USA

Trevor Mamer
School of Engineering Technology,
Purdue University
West Lafayette, Indiana, USA

ABSTRACT

Dielectric electroactive polymers are materials capable of mechanically adjusting their volume in response to an electrical stimulus. However, currently these materials require multi-step manufacturing processes which are not additive. This paper presents a novel 3D printed flexible dielectric material and characterizes its use as a dielectric electroactive polymer (DEAP) actuator. The 3D printed material was characterized electrically and mechanically and its functionality as a dielectric electroactive polymer actuator was demonstrated. The flexible 3-D printed material demonstrated a high dielectric constant and ideal stress-strain performance in tensile testing making the 3-D printed material ideal for use as a DEAP actuator. The tensile stress- strain properties were measured on samples printed under three different conditions (three printing angles 0°, 45° and 90°). The results demonstrated the flexible material presents different responses depending on the printing angle. Based on these results, it was possible to determine that the active structure needs low pre-strain to perform a visible contractive displacement when voltage is applied to the electrodes. The actuator produced an area expansion of 5.48% in response to a 4.3 kV applied voltage, with an initial pre-strain of 63.21% applied to the dielectric material.

INTRODUCTION

In small scale systems, such as micro robots and other portable micro devices, the conventionally used electromagnetic actuators generally have poor efficiencies. During the last two decades, the topic of electroactive polymers has been growing in an attempt to improve the efficiency of small scale actuators. Recently, there has been increased interest in electroactive polymer actuators (soft actuators) due to their lightweight structure, easy fabrication and low cost. Electroactive polymers exhibit a change in size or shape when stimulated by an electric field. This type of material can have several configurations but are generally divided in two classes: Electric and Ionic.

- Electric EAP's are materials in which actuation is caused by electrostatic forces between two electrodes, which squeeze the polymer. These types of materials are capable of very high strains and are fundamentally capacitors. Electric EAP's change their capacitance when voltage is applied, causing the polymer to compress in thickness and expand in area due to the electric field. This type of electroactive polymers is known as "Dry" and requires high voltages to be actuated (1 – 5 kV), but very low electrical power consumption [1].

- Ionic EAP's are materials in which actuation is caused by the displacement of ions inside the polymers. These types of materials are known as "Wet" and require low voltages to be actuated [1 – 5 V], but higher electrical power consumption. Some types of Ionic materials need to maintain moisture content to perform correctly [2].

The structure of a soft dielectric EAP consists of a thin dielectric film, which is coated on both sides with a conductive material. When applying a DC high voltage U (in the range of thousands of volts), the electrodes squeeze the elastomeric dielectric in the thickness direction, resulting in a mechanical pressure. For volume to be conserved, the incompressible elastomer film expands in the planar direction to compensate for the decrease in thickness. The stress induced by electrostatic attraction is known as "Maxwell stress".

$$P_{equivalent} = \varepsilon_0 * \varepsilon_r * \left(\frac{U}{d}\right)^2 \qquad (1)$$

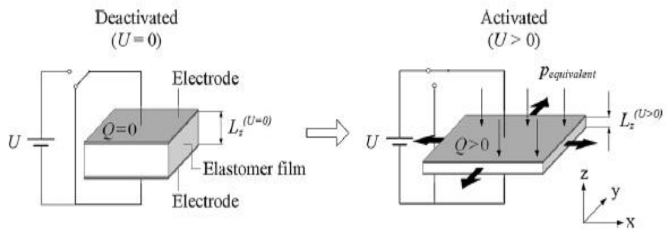

Figure 1. Structure and working principle of soft dielectric EAP (Q = electrical charge) [3].

As soon as the voltage is switched off and the electrodes are short circuited the film deforms back to initial state. The actuation of the dielectric elastomer's films can be used in two different ways:

1. Work in the planar directions (expanding actuator)
2. Work in the thickness direction (contractile actuator

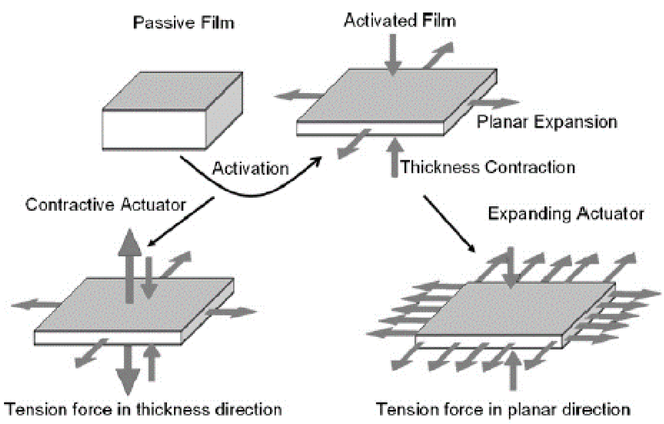

Figure 2. Activation modes: extending with contractile [3].

To increase the absolute deflection of dielectric elastomer actuators at limited driving voltage, thin dielectric films and electric electrodes are stacked on top of each other using a multilayer fabrication technology. The design of the pile-up actuator is based on a series of capacitors electrically connected in parallel with alternating polarities in each layer. When a voltage is applied between two electrodes, an external tension force can be transmitted by the electrostatic field induced Maxwell forces. As a result, the dielectric film is squeezed by both neighboring electrodes, and contractive motion of the entire actuator occurs. The external tension force has to be transmitted over the electrode layer by inducing tensile stresses inside the electrode material. This can easily be accomplished when the dielectric medium is made of compressible elastic material. In such a case, no planar expansion occurs when the dielectric is compressed by the Maxwell forces and therefore the electrodes can be made of a solid conductive material layer. When using incompressible materials like hyper-elastic elastomer films as the dielectric, the electrode has to be compliant in the planar direction in order to allow unrestricted planar expansion of the dielectric film without reducing the electric conductivity needed to provide the electrostatic field, even in the deformed state. Configuration and structure of the DEAP's is very versatile allowing for design of actuators with different configurations and actuation modalities [4].

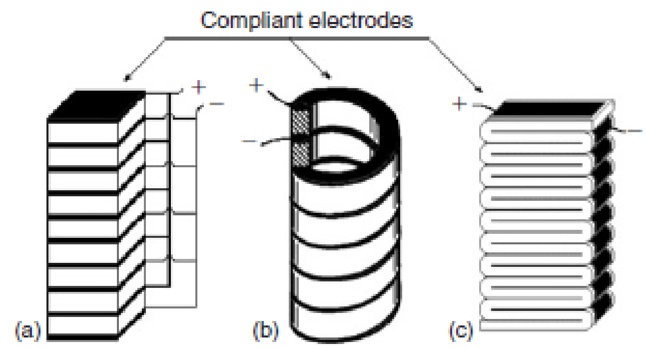

Figure 3. Configuration of DEAP's actuators: (a) basic stack, (b) helical, (c) folded [5].

NOMENCLATURE

P_equivalent = Equivalent pressure
U = Voltage
d =Thickness of the dielectric films
ε_0 = Free space permittivity (8.85 x 10^-12 F/m)
ε_r = Relative permittivity of the dielectric material

3D PRINTING

Elastomer films can be made by casting, dipping, spin coating, or spraying, but these types of manufacturing processes can take a long time and the fabrication processes are difficult, expensive, and/ or labor-intensive. 3D printing seeks to improve the fabrication speed, accuracy and consistency of the elastomer films [6]. In addition, the 3D printing process allows one to manufacture a large number of layers continuously, resulting in better performance of the actuators.

Fused deposition modeling (FDM), generally called fused filament fabrication (FFF), feeds a plastic filament into a heated extruder and then precisely lays down the material following predetermined coordinates dictated by the desired structure to be printed. This type of manufacture process is versatile and adaptive, allowing one to extrude a great variety of materials. This type of 3D printing allows one to make prints composed of more than one material in the same print, making it possible to print the dielectric film and the electrodes at the same time. Furthermore, it facilitates the manufacturing and experimentation of new materials, which can be extruded in a simple way to obtain the filament of the desired material. The dielectric films used for the tests were 3D printed using this type of manufacturing process [7].

PRE-STRAIN

Several types of dielectric elastomers have been investigated and are particularly attractive for large strain and high-power applications. Electro elastomers based on acrylic copolymer elastomers (e.g., 3M VHB 4910) and complaint electrodes have been shown to exhibit electro mechanical strains of up to 380% in terms of area expansion. Furthermore, the specific elastic energy density (3.4 J/g), stress (up to 8 MPa), and electromechanical conversion efficiency (60-90%) are all extraordinarily high. However, this performance is only observed when the acrylic films are highly pre-strained. Pre-strain is commonly used to improve the overall performance of DEAP's. The pre-strain enhances the dielectric breakdown of the elastomer films and realigns defects that could be responsible for premature dielectric breakdown [8]. The pre-strain increases the response speed, induces preferential expansion when asymmetrically stretched and reduces the thickness hence enhancing the stress/strain response at lower applied voltages.

The mechanical properties of plastic materials depend on both the strain and temperature. At low strain, the deformation of most solids is elastic – the deformation is homogenous and after removal of the deforming load the material returns to its original size and shape. In this regime, the stress is proportional to the strain. Elastomer materials present the highest range of elastic behavior, making these types of materials the best option for dielectric films. In addition, elastomer materials can achieve large deformations in a small range of stress when the material is pre-strained [8].

THERMOPLASTIC POLYURETHANE (TPU)

Thermoplastic polyurethane (TPU) are a class of materials capable of demonstrating plastic deformation under thermal loads while also exhibiting elastic behavior under mechanical loads. This material presents a dielectric constant (relative permittivity) between 4 and 8, making this material ideal for use as dielectric films [9]. The dielectric constant is a unitless parameter comparing the permittivity of a material to the permittivity of free space.

The dielectric elastomer films were made using TPU, a soft filament with a shore hardness of 60A. This material is the softest filament available on the market, it feels like a rubber band, and produces finished parts that are completely tactile, flexible, and highly functional for applications that require stretch and flexibility.

TENSILE TEST

Tensile tests were carried out to characterize the properties of the material and the influence of two parameters: the printing angle and the number of layers. The properties were measured on samples printed under three different conditions (three printing angles 0°, 45° and 90°). Specimens were tested according to ASTM D638 "Standard Test Methods for Tensile Properties". MTS universal loading machines were used to conduct the tensile testing, using a load cell of 1 kN. The MTS wedge grips were displaced at a rate of 50 mm/min with data collected at 100 Hz.

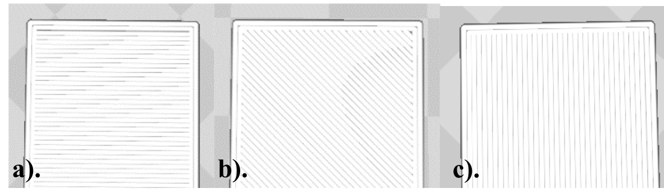

Figure 4. Printing angles: a). 0°; b). 45°; c) 90°.

3D Printed Specimen

Each specimen was individually measured (thickness and width) at several locations throughout the test section. According to the ASTMs, the smallest cross-sectional area was used to determine appropriate stress values. All the specimens were 3D printed using FDM. The extrusion temperature was set to 215°C and the bed was heated to 60° C. Two types of specimens were printed and tested, varying the number of layers (one layer (thickness 1.00 mm) and five layers (thickness 0.2 mm each layer)). The specimens were type IV, based on the ASTM norm, generally used when direct comparison is required between materials in different rigidity cases. Five specimens per printing angle for each type of specimens were tested, for a total of 30 samples tested.

DIELECTRIC ELECTROACTIVE POLYMER ACTUATOR

PERCENTAGE OF ELONGATION

It's necessary to stretch the samples to induce pre-strain in the dielectric material and obtain a better performance in the actuation. An Iris Stretcher developed in the laboratory is a machine capable of applying a uniform multi-directional load to round specimens of dielectric elastomers, in order to extract mechanically pre-strained samples to manufacture electroactive polymers. The iris stretcher was used to pre-strain samples to test the materials functionality as electroactive polymer actuators and the percent elongation achievable.

3D Printing Samples for Electroactive Polymer Actuator Testing

All the samples were 3D printed. The extrusion temperature was set in 215°C and the bed was heated to 60° C. The samples are circles of 10 cm in diameter and 0.2 mm of thickness, with an external ring of 1.5 cm and 0.8 mm of thickness. Each layer has a thinness of 0.2 mm.

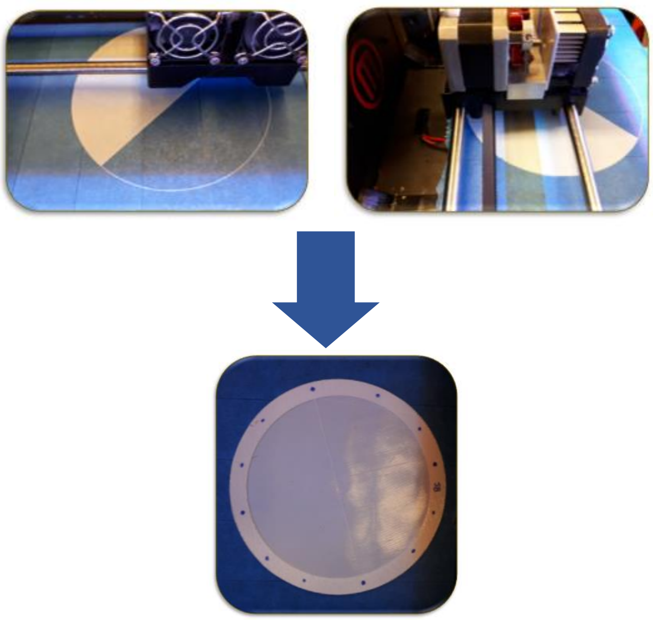

Figure 5. 3D Printing of Dielectric material using fused deposition modeling (FDM).

Elongation Test

The samples were clamped to each arm of the Irish Stretcher machine. Then, the samples were stretched in the planar directions at the same velocity at each clamped point. Ten samples were tested. Results showed that the samples are capable of elongating 400 ± 20%, in the diameter directions, before failure.

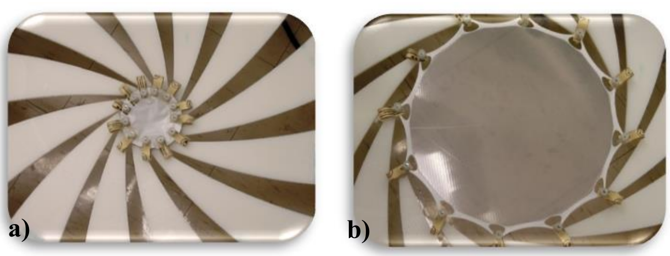

Figure 6. Elongations test a). Before stretch b). After stretch (elongation of 490%).

MANUFACTURING PROCESS

The dielectric elastomer film discs were 3D printed, using the same settings and dimension as in the elongation test samples. All the samples were stretched using an Irish stretcher machine. The samples were glued to an acrylic ring after the stretching process in order to maintain the strain in the inside area of the ring. Carbon conductive grease was used as electrode material and scattered on both sides of the dielectric film in a circular layer of 5 cm in diameter. Conductive copper tape was used on both sides as a conductor between the electrodes and the high voltage supply.

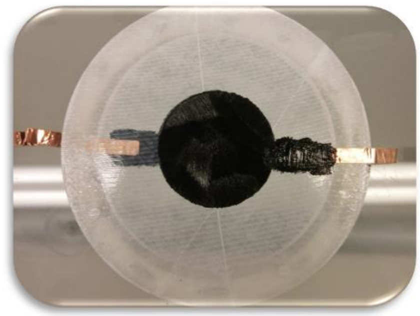

Figure 7. Dielectric electroactive polymer actutor structure.

EXPERIMENTAL CHARACTERIZATION

All the DEAP actuators were tested using a high voltage supply. This machine can give a maximum voltage of 10 kV, the current was limited to below 1000 µA. The tests were performed by increasing the voltage gradually in 10 volts intervals until the electrical breakdown. The stretching process and voltage test were recorded and analyzed using the software "Tracker (Video Analysis and Modeling Tool)", finding the pre-strain, the percentage of area expansion and the voltage breakdown.

The experimentation was based around two stages. The first stage was to identify the relationship between pre-strain and voltage breakdown in order to determine the pre-strain necessary to increase the voltage breakdown and the motion of the actuator. The second stage was to measure and replicate the response of five actuators, using the pre-strain found in the first stage for all the structures, analyzing the percentage of area expansion and the voltage breakdown.

RESULTS

TENSILE TEST

The key specifications of the specimens tested for the tensile test are describes in the following tables. Peak load, peak stress, strain at break and Young's modulus were determined for each type of specimen testes.

Table 1. Key data of the Tensile Test – One-layer specimens

	Specimens - One Layer				
Printing Angle	Number of samples	Peak Load [N]	Peak Stress [MPa]	Strain at Break [mm/mm]	Young's Modulus [MPa]
0°	5	50.95	8.9	5.96	5.36
45°	5	53.13	11.2	7.96	3.16
90°	5	116.59	26.2	6.58	3.99

Table 2. Key data of the Tensile Test – Five layers specimens

	Specimens - Five Layers				
Printing Angle	Number of samples	Peak Load [N]	Peak Stress [MPa]	Strain at Break [mm/mm]	Young's Modulus [MPa]
0°	5	46.94	9.7	5.94	5.12
45°	5	50.67	10	7.02	2.87
90°	5	103.42	22.7	6.68	3.42

As expected, the material presents a different response depending of the printing angle and the numbers of layers. The performance of these types of electroactive structures depends on the angle of impression, a parameter that determines the elastic modulus of the dielectric film. When the printing angle is parallel to the load direction, the material presents greater resistance to traction. On the contrary, the greater the perpendicularity of the printing angle and the load direction, the less resistance the material presents.

The number of layers of the specimen affects its traction behavior. In general, the samples with a single layer presented a greater resistance to the load and greater deformation. This may be due to a better adhesion in the infill of the samples, and the absence of gaps, usually present in impressions with more than one layer. Figures 8 shows the average response for the samples with one layer and a printing angle of 45°.

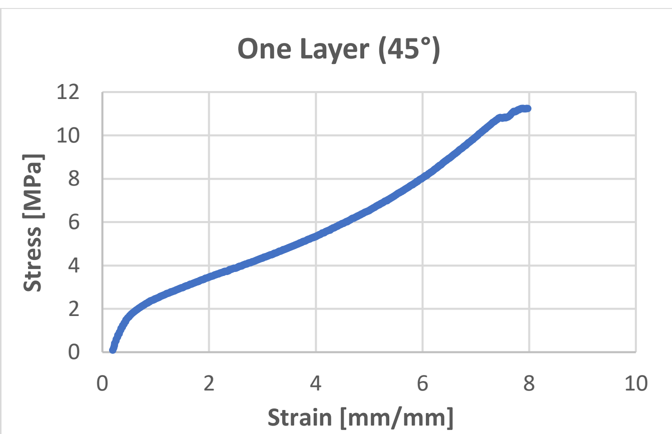

Figure 8. Specimen with one layer and printed angle of 45°

Figure 8 shows the expected behavior for an elastomeric material, presenting large deformations in a short range of stresses due to its low Young's modulus. This is evident that the pre-strain takes the material to the elastic zone where, with low stress, the material presents greater deformation, improving the performance of the actuator.

PRE-STRAIN EFFECT

To determine the percentage of pre-strain best suited to obtain a better response of the electroactive structure, 9 samples were tested varying the percentage of pre-strain and measuring their respective voltage breakdown. Figure 9 shows the effect of the pre-strain in the dielectric material versus the voltage breakdown of the sample. Three samples were tested with the same pre-strain, having three different values of pre-strain (63%, 360% and 860%), resulting in a great range of the parameter of interest.

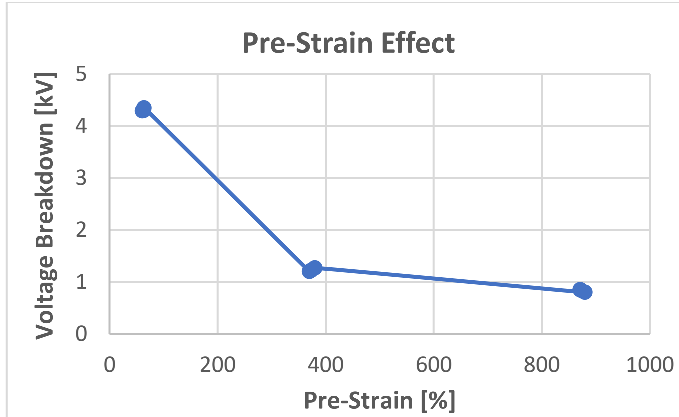

Figure 9. The pre-strain effect on the voltage breakdown.

Based on the previous figure, it is possible to infer that the electroactive structure increases its resistance to voltage when it is pre-strained at a low percentage, approximately 63%. This value of pre-strain is adequate to improve the performance of the structure and maintain a good resistance to the electric field created by the electrodes. Likewise, it is observed that increasing the pre-strain of the dielectric material reduces the resistance to the electric field, in turn reducing the dielectric thickness.

DEAP ACTUATION

Five electroactive structures were analyzed under the same pre-strain conditions to validate that the structures are replicable and presents a similar behavior. The dielectric films were pre-stretched by 63%, analyzing the percentage expansion of the active area (equivalent to the area of the electrodes). The value of the area expansion percentage is taken just before the rupture of the dielectric material by the electric field.

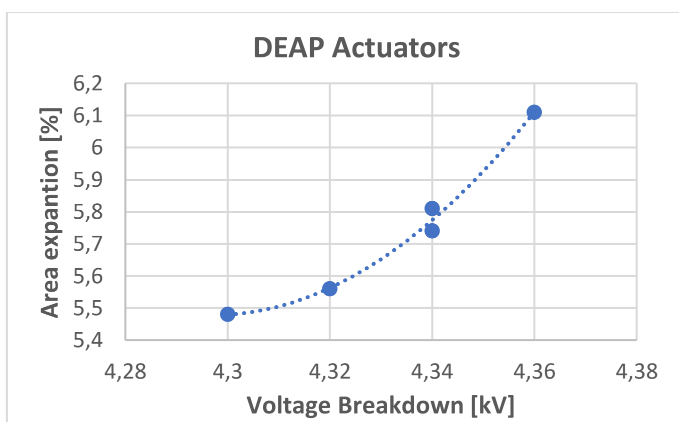

Figure 10. Area expansion of the dielectric electroactive actuators.

Based on previous figure, it is possible to analyze that the response of the 3D printed DEAP actuators is consistent and replicable, obtaining similar motion responses for all the samples tested and validating the manufacturing process. The average expansion area percentage of the electro active structure was 5.75%. The performance of the actuators was adequate, presenting a movement visible to the human eye. It is important to mention that in many occasions these types of structures present deformation in the micro scale. Figures 11 and 12 shows the video analysis of the actuation of one sample using the software “Tracker” which is a free video analysis software capable of calculating deformations [11].

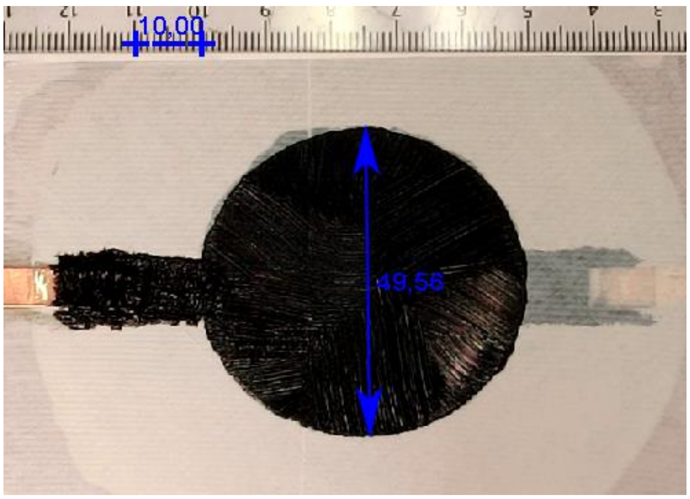

Figure 11. Diameter of the active area before actuation.

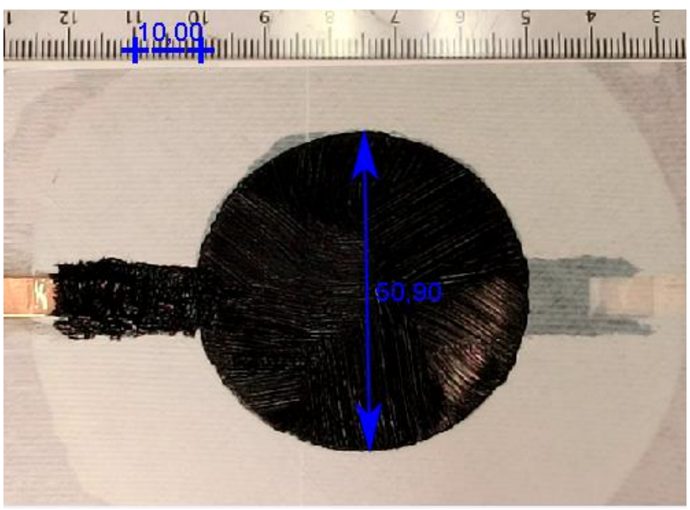

Figure 11. Diameter of the active area after actuation.

CONCLUSIONS

A novel design of an electroactive dielectric actuator is presented, whose manufacturing process improves its performance based on the pre-strain of the dielectric film. The manufacturing process uses 3D printing to produce dielectric films. These types of films are characterized, analyzing the influence of the angle and the quantity of layers of the dielectric material, determining that the resistance of the structure to external loads depends on the orientation in which the material is printed. Through traction tests, it is possible to analyze the characteristic behavior of the material providing evidence of the importance of pre-strain in this type of electroactive structure. The pre-strain of the electrical material allows the electroactive structure to present greater deformations with smaller stresses, in its zone of elastic behavior.

The design of the actuator presented requires a 63% pre-strain to improve its performance and resistance to the electric field. Under these manufacturing conditions, the actuator has an expansion of its active area of 5.75% and a breaking voltage of 4.3 kV. On the other hand, the 3D printed dielectric material presents a performance similar to others electroactive structures analyzed that use VHB as dielectric material, being this the most common material for these types of actuators. Finally, it is possible to affirm that it is viable to manufacture a dielectric structure using 3D printing as a manufacturing process. Achieving 3D printing of innovative flexible materials and opening the possibility to print flexible conductive materials, in order to print the entire structure of the actuator using 3D printing.

ACKNOWLEDGMENTS

This work was sponsored in part by the National Science Foundation under grant CNS-1726865.

REFERENCES

[1] Elaine Biddiss, T. C. (2007). Dielectric elastomers as actuators for upper limb. *ELSEIVER*, 16.
[2] Ron Pelrine), R. K. (1999). High-field deformation of elastomeric dielectrics for actuators. *ELSEIVER*, 12.
[3] G. Kovacs∗, L. D. (2009). Stacked dielectric elastomer actuator for tensile force transmission. *ELSEVIER*, 9.
[4] Farah Afiqa Mohd Ghazalia, C. K. (2016). Soft dielectric elastomer actuator micropump. *ELSEIVER*, 9.
[5] Kornbluh, R. (2009). *FUNDAMENTAL CONFIGURATIONS FOR.* Menlo Park, CA, USA: SRI International.
[6] Helmut F. Schlaak, P. L. (2011). *MULTILAYER STACK CONTRACTILE.* Darmstadt, Germany: Darmstadt University of Technology.
[7] Letcher, T. (2014). Material Property Testing of 3D-Printed Specimen in PLA on an Entry. *ResearchGate*, 9.
[8] Soon Mok Ha1, W. Y. (2007). Interpenetrating networks of elastomers. *Smart Materials and Structures*, 9.
[9] Polyurethanes, P. C. (20 de 04 de 2018). Innovative material properties. Obtenido de https://www.tpu.covestro.com/en/Technologies/Properties/Electrical-Properties
[10] O.A. Araromia, ∗. A. (2011). Spray deposited multilayered dielectric elastomer actuators. *ELSEIVER*, 9.
[11] Tracker - Video analysis and modeling tool. (2018). Douglas Brow

