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The effect of folds in thin metal film electrodes used in dielectric elastomer actuators

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ABSTRACT

Due to high electrical conductivity, metals have been the traditional material for electrodes. However, as metal films have low fracture strains, they are not commonly used as compliant electrodes in the field of dielectric elastomer actuators and generators. We have recently demonstrated that the use of metal films as electrodes can in fact allow dielectric elastomer actuators to have large actuated area strains of more than 100%. The metal film electrodes used have a network of crumples that unfolds as it is subjected to in-plane strains. This mechanism enables the metal electrodes to have a relatively low stiffening effect on the soft dielectric elastomer and to be able to retain its low resistance despite being highly strained; the latter characteristic would facilitate in the reduction of parasitic losses in dielectric elastomer generator applications. By metalizing a highly bi-axially pre-stretched dielectric elastomer that was subsequently partially relaxed, a bi-axial compressive force was introduced into the metal films, thereby causing a network of folds to form. In this paper, we study the change in the topography of the crumpled metal electrodes as the metal films are subjected to varying extents of bi-axial compression. It was also found that the way in which the metal films fold does in fact alter the electrodes' stretchability, as manifested in the performance of the dielectric elastomer actuators using these crumpled metal films as electrodes.

Keywords: Dielectric elastomer actuator, metal electrodes, crumples, folds, corrugations

1. INTRODUCTION

Dielectric elastomer actuators (DEAs) and dielectric elastomer generators (DEGs) require highly compliant and stretchable electrodes. Unlike traditional electrical conductors, these electrodes need to offer low mechanical and electrical resistance even when subjected to high tensile strains. Traditionally, metals have been the obvious material choice for electrodes due to their high electrical conductivity. However, such a choice is not so obvious in the case of stretchable electrodes for use in DEAs and DEGs, because freestanding metal films have been known to have very low fracture strains of less than 2% [1]. In addition, most metals are very stiff, with a Young's modulus in the Giga-Pascal range, and can hence oppose actuation forces, thereby limiting actuated strains in DEAs.

With low fracture strain and high stiffness, DEAs using metal electrodes [2, 3] are expected to have poor actuated strain performances. To improve the fracture strain of the metal electrodes, PolyPower has proposed and developed corrugated metal electrodes for use in DEA. Such corrugated electrodes were prepared by depositing silver on the corrugated surface of a moulded elastomer substrate and can be stretched only along one axis. DEAs using the corrugated electrodes can produce a linear actuated strains of less than 15% [4]. However, a higher actuation strain is desired from the metalized DEA. Recently, we have prepared crumpled metal electrodes that enables DEAs to attain a larger actuated area strains up to 100% at a driving voltage of only 1.9kV [5]. Such a performance was possible because the network of crumples unfolded when subjected to in-plane strains, thereby enabling the metal films to have a relatively low stiffening effect on the soft dielectric elastomer and to be able to retain its low resistance despite being highly strained.

In our work, the network of folds in each metal electrode was formed due to the presence of a bi-axial compressive force that was introduced during the fabrication process: a thin metal film layer was deposited onto a highly bi-axially pre-stretched dielectric elastomer that was subsequently partially relaxed. The resulting topography of the electrodes depend on both the magnitude of the substrate's pre-stretch and on the amount of compressive strain in the skin [6]. In this paper, we study the change in the topography of the crumpled metal electrodes as the metal films are subjected to varying extents of bi-axial compression. It was also found that the way in which the metal films fold does in fact alter the electrodes' stretchability, as manifested in the performance of the dielectric elastomer actuators using these crumpled metal films as electrodes.

2. EXPERIMENTAL

The amount of compressive strain in the metal film electrodes affects its topography, which in turn affects the strain performance of the DEA using such electrodes. The electromechanically activated strains of DEAs using crumpled metal electrodes with varying degrees of compressive strain were studied. In addition, the sheet resistance and stiffness of the crumpled metal electrodes were determined from uni-axial stretch tests in order to gain an insight into the reason for such behaviour.

2.1 Fabrication of the Crumpled Metal Electrodes

As shown in Figure 1, the crumpled metal electrodes were formed in a few process steps. First, a dielectric elastomer film was pre-stretched. Afterwards, a thin metal film was then deposited onto the surface of the stretched dielectric layer. Subsequently, the pre-stretch in the dielectric layer was partially relieved in order to introduce a compressive strain in the metal film.

The aim of this paper was to study the effects of folds in the metal film electrodes on DEA performance, while the folds were affected by the extent of bi-axial compression in the metal film. As such, during fabrication, it was made sure that while the amount of compressive strain in the metal film was varied, the final dielectric elastomer pre-stretch (iv) in relation to the initial dielectric elastomer (i) was kept constant. This was carried out in order to minimise the effects of dielectric pre-stretch on the performance of the DEA.

Figure 1: Schematic of the fabrication of the crumpled metal electrodes in a cross-sectional view. i) Pre-stretching of the dielectric layer. ii) Deposition of the metal film onto the dielectric layer. iii) Partial relaxation of the pre-stretch in the dielectric layer and simultaneous introduction of compressive strains in the metal film. iv) Crumpled metal electrode.

The dielectric elastomer used was the acrylic elastomer from 3M's VHB series while the metal films were formed by the electroless deposition of silver (ELD silver). First, the acrylic elastomer was cut to form a circle (between 36 and 72 mm in diameter). Next, sixteen circumferential points on the circular elastomer were attached to a custom made setup in order to stretch it radially (between 150% and 400%). Following that, the centre region of either side of the stretched elastomer was coated with ELD silver films. The electroless deposition of silver was carried out in a manner similar to previous experiments conducted by our group [7]. Each ELD silver film covered a 100 mm and a 10 mm diameter circular area for the uni-axial stretch test samples and the electromechanical activation samples, respectively. Subsequently, the tension, still held at sixteen points, was gradually released to a desired pre-stretch level: zero pre-stretch for the uni-axial tensile experiments and 150% bi-axial pre-stretch for the electromechanical activation experiments.

2.2 Electromechanical activation experiments

For the electromechanical activation tests, the 250 μm thick VHB 9473PC was used as the dielectric layer. Three samples were tested for each of the five compressive strain values of 0%, 20%, 30%, 40% and 50%. Here, compressive strain is defined as reduction in electrode size in relation to its original size. In other words, by referring to Figure 1, compressive strain is $(A_o - A') / A_o$. Each membrane DEA had a remaining pre-stretch of 150% by 150% and was supported by a square acrylic frame. The electrodes on both sides of the membrane were connected to a high voltage source (610E, Trek Inc.) by thin aluminium foil electrical leads and crocodile clips. A digital camera (Canon EOS 550D) fitted with a macro lens (Tamron AF 90mm f/2.8 Di SP A/M 1:1 Macro Lens) was used to take still photographs of the top view of the electrodes, which were then analysed using MATLAB's Image Processing Toolbox (2009a, The MathWorks), in order to calculate the change in electrode area. The voltage and current across the DEA, with respect to time, was logged by means of a data acquisition card (PCI 6052E, National Instruments).

2.3 Uni-axial tensile experiments

While radial stretch tests give a more representative indication of the stiffness and resistance of the electrodes during electromechanical activation, only uni-axial stretch measurements could be obtained due to equipment limitations. Nevertheless, these results would be able to give an indication of the reasons behind the electromechanical activation performances. Here, 500 μm thick VHB 4905 was used as the dielectric layer. Each strip of electrode was clamped at its two ends by two pairs of acrylic plates, such that the middle segment was free to be uni-axially stretched. Two electrical leads were clamped as well, beneath the acrylic plates, in order to measure the electrical resistance of the free segment of the electrode, which was 25.4 mm by 25.4 mm in area. A tensile tester (Instron 5565) was used to uni-axially stretch the sample at a rate of 3 mm per minute, whilst monitoring its force and extension. Resistance across each electrode was measured using a digital multimeter (34410A, Agilent Technologies) using the four-wire probe configuration. From the logged force and extension data for unidirectional loading, a stress-strain curve was obtained. The Young's modulus of the electrode was then determined by using the finite difference method to find the gradient at each state of compression.

3. RESULTS AND DISCUSSION

3.1 Change in the Metal Film Electrode's Topography with Varying Compressive Strains

Figure 2 shows the topography of the ELD silver films when subjected to varying amounts of bi-axial compression. At close to 0% compression, the metal film was relatively flat, with only slight wrinkles that formed due to handling when mounting the sample for imaging. At 20% compressive strain, it is apparent that a network of folds had formed. These folds might have contributed to lowering the stiffening effect of the silver film on the dielectric layer, as they are able to unfold when stretched. At 40% compression, the two-dimensional network of folds become much more intricate and at 50% compression, a new hierarchy of folds appear to have formed. The transition of the topography of the silver film is marked and the different fold features are likely to play a major role in the varying performance of the electrodes.

Figure 2: Micrographs show the change in topography of the metal film electrode as it is subjected to increasing amounts of bi-axial compressive stress.

3.2 Effect of Compressive Strain on DEA electromechanical activation performance

In order to study the effects of folds in metal film electrodes, electromechanical activation tests were conducted on membrane DEAs using ELD silver electrodes subjected to different starting compressive strains. Here the performance measure used was the expansion of the electrode area due to electromechanical activation, as shown in Figure 3. As one of the merits of such electrodes is their ability to allow the DEA to produce large strains at relatively low voltages, only the maximum actuated area strain at less than 2kV of driving voltage was taken into consideration. The actuated area strain for each sample was plotted against driving voltage, as shown in Figure 4. Subsequently, the maximum actuated area strain for each sample was plotted with respect to the amount of compressive strain in the metal electrodes, as shown in Figure 5.

Figure 3: The area strain of a membrane DEA was taken to be the difference in electrode area, during activation (right) and when passive (left), with respect to the passive electrode area (left). The white ink around the electrode was applied in order to facilitate image processing for finding the change in electrode area.

Figure 4: The actuated area strain versus driving voltage of five different samples at five different compressive strains.

Actuated strains improved with increasing amounts of compressive strain in the silver electrodes and this trend continued up to 40% compressive strain. However, there appears to be a turning point after 40% at which the DEA performance decreased quite sharply. This might have been caused by an increase in stiffness of the electrodes that might have been caused by the fold structures in the silver film. In order to better understand these phenomena, the resistance and stiffness of the silver electrodes were also studied as they were subjected to different amounts of compressive strain.

Figure 5: Maximum actuated area strain of membrane DEAs using ELD silver film electrodes subjected to different initial compressive strains. The maximum strain was limited to that obtained at voltages less than 2 kV. Three samples were tested per compression value and the error bars indicate the range.

3.1 Resistance

Based on uni-axial stretch tests, it was found that the resistance of the silver electrode decreased as it was subjected to increasing amounts of compressive strains, as shown in Figure 6. In addition, the sheet resistance of these electrodes was less than $1\text{k}\Omega$ when subjected to 12% or more compressive strain. This relatively low resistance would facilitate the reduction of parasitic losses if used in DEG applications.

Figure 6: Sheet resistance reduced with the increase in uni-axial compression of the silver electrodes.

3.2 Stiffness

The electrodes used in DEAs need to have a low stiffness in order to avoid limiting the actuated strain during electromechanical activation. In order to get an idea of how the compressed silver electrodes stiffens the soft dielectric elastomer, the stress-strain relationships were first determined from uni-axial tensile tests. The tests were carried out on a VHB 4905 strip with silver electrodes at an initial bi-axial compressive strain of 71%, as well as a plain VHB 4905 strip that served as a comparison. It is obvious, from Figure 7, that the silver coated VHB strips are stiffer than the uncoated ones.

Figure 7: Uni-axial tensile tests conducted show the stress-strain relationships for the silvered VHB 4905 strip with 701%-initial compression and the plain VHB 4905 strip. It is apparent that the silver coated strips are stiffer than the uncoated ones.

The instantaneous Young's Modulus, as the metal electrodes were under different amounts of compressive strain, was determined by using the finite difference method on the stress-strain relationships at the different states of strain, as shown in Figure 8. It appears that the Young's Modulus of the crumpled silver film on the dielectric elastomer decreased from 0 to about 25%, after which it increased.

Figure 8: Instantaneous Young's Modulus of the crumpled silver film at varying amounts of compressive strains.

It is recognised that even at 0% uni-axial strain, which corresponds to a 71% compression of the silver film, the VHB elastomer is under tension due to the compressive stresses of the crumpled silver films. However, in the analysis of the Young's Modulus values, these internal stresses were neglected. In other words, the crumpled metal film on elastomer composite was seen as a unit, and hence the Young's Modulus of the VHB elastomers, both plain and with crumpled silver, were compared based on the amount of external stress applied to them. With that in view, in an attempt to isolate the stiffening effect of the crumpled silver on the VHB elastomer, the difference in the Young's modulus of the two were found, and the stiffening effect was taken to be the ratio of that difference to the Young's modulus of the plain VHB elastomer. This ratio changes over varying amount of compressive strain in the electrodes, as shown in Figure 9. The stiffening effect seems to decrease with increasing amounts of compressive strain, up to 25%, after which it increases. This indicates that while an increase in the amount of compressive strain in the metal electrodes brings about a decrease in the stiffening effect, there is a turning point at which further increasing the compressive strain in the metal electrodes would caused the stiffening effect to increase. This trend is similar to what was observed in the electromechanical activation tests, wherein the maximum actuated strain increased up to 40% compressive strain and decreased thereafter. This strongly indicates that stiffness had a part to play in the performance of the crumpled metal electrode DEAs.

Figure 9: The stiffening effect is taken to be the ratio, of the difference between the Young's Modulus of the VHB elastomer with the crumpled silver films and that of the plain VHB elastomer, to the Young's modulus of the plain VHB elastomer. This stiffening effect gives an indication of the apparent stiffening of the VHB elastomer by the crumpled silver film at varying amounts of compressive strains.

4. CONCLUSIONS

DEAs using metal-film electrodes can have large actuated area strains at low voltages if the electrode have a low stiffness and remain conductive during electromechanical activation. Such electrodes can be obtained by simply introducing a network of crumples that unfolds as it is subjected to in-plane strains. The forms of these crumples or folds are affected by the amount of bi-axial compressive strain in the metal film, which in turn affects the strain performance of DEAs using such electrodes. The sheet resistance of the electrodes was found to decrease with increasing compressive strain in the metal film and that can be beneficial to reducing parasitic losses, especially when used in DEG applications. The stiffening effect of the metal film on the dielectric layer was also found to decrease with increasing compressive strain, but only up to a point, after which it increased. This was reflected in the DEA actuated strain performance. Currently, we are still unable to determine how the topography of the crumples in the metal film affects the stiffness and hence the performance of the electrodes. However, it is an extremely interesting area of study that would be worthy of pursuit.

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