

# Electrode structures in high strain actuator technology

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Dielectric elastomers are a class of electro-active polymers (EAPs) which have been used for smart structures, such as muscle-like actuators. These materials with compliant electrodes are transducers of electrical to mechanical energy, with extremely large strain and good efficiency. A thorough understanding of the physics underlying the nature of different electrode materials can help modify actuator response. The objective of this paper is to investigate the effect of 4 different electrodes (graphite powder, carbon filled grease, silver filled grease and electrically conductive silicone rubber) on the performance of dielectric elastomer actuators. The principle of operation, the method of fabrication and test method of planar actuators are discussed. Effects of different driving voltages and different prestrain values on the actuator response have been studied. Electrical conductivity under strain, electrode surface uniformity and mechanical compatibility with substrate, as the most important parameters of the electrodes, has been investigated. The importance of latter case in terms of curing state and thickness of rubber electrode has been studied, as influential factors in actuator response. Electromechanical coupling efficiency was used as a consequential parameter to compare different electrode performances. It is concluded that this parameter is influenced by the nature of electrodes.

(Received September 24, 2007; accepted November 1, 2007)

*Keywords:* Compliant electrode, Dielectric elastomer actuator, Electro-active polymer

## 1. Introduction

In general, polymers are attractive as actuator materials because they are lightweight, easily fabricated in various shapes, low cost, have tailor made induced properties and etc. Within the general category of polymers, electro-active polymers (EAPs) are promising as a general-purpose actuator technology with good overall performance. These polymers are often described as artificial muscles because their performance is comparable to that of natural muscle and likewise are scale invariant.[1,2] Dielectric elastomers (DEs) as one of the EAPs are functional materials that can be used as actuators in active structures, in particular, when large deformations are required. More than 300% strain has been obtained from dielectric elastomer actuators. [3-7] Such actuators could be used for many applications, like an optical switch, in which an opaque electrode area interrupts a light beam when actuated. Large aperture mirrors would also be fabricated from these structures for spatial and terrestrial optical systems. [8] Research in this emerging field has focused so far on the selection of suitable elastomers, actuator configurations, electrode structures and so on. [8-11, 12, 13]

It has been well known for many years that the electric field pressure due to free charges on the surface of all insulating materials induces stresses (Maxwell's stress) that strain the material. More recently it has been found that this mechanism of actuation can produce powerful electro-active responses in DEs. When a DE is coated on each side with a compliant electrode material, a simple 3-layer structure will be built. When a voltage is applied across the two electrodes, the electrostatic forces compress and stretch the film (Figure 1). Compression of the film

thickness brings opposite charges closer together, whereas planar stretching of the film spreads out similar charges.[13] This mechanism converts electrical energy to mechanical energy and provides actuation. As a result, the polymer material is enlarged elastically in the plane. The Maxwell stress  $\sigma$  acting on the elastomer film can be calculated for a given applied voltage  $V$  and film thickness  $z$  by Equation 1: [1]

$$\sigma = \epsilon_r \epsilon_0 E^2 = \epsilon_r \epsilon_0 \left( \frac{V}{z} \right)^2 \quad (1)$$

Where  $\epsilon_0$  is the free space permittivity ( $8.85 \times 10^{-12} \text{ F/m}$ ) and  $\epsilon_r$  is the relative dielectric constant of the elastomer. As Equation 1 shows, the stress is inversely proportional to the square of the thickness. Applying pre-strain, among other benefits, is a convenient way to reduce the thickness of the film and subsequently increase the stress. [10, 13, 14]

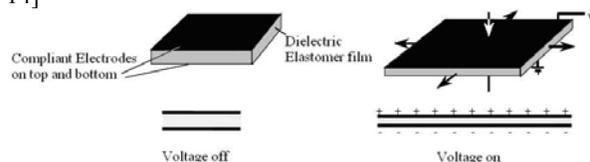


Fig. 1. Dielectric elastomer film before (left) and after actuation (right).

The strain produced by the applied electric field is the other important property of DE actuators. To accommodate high strain during actuation, the electrodes should deform without imposing preferably any restrains,

while maintaining their conductivity. In other words electrodes have to be softer or at least compatible with dielectric elastomer in their mechanical properties. An ideal electrode would be highly conductive, perfectly compliant and could be made thin relative to the polymer thickness, in order to provide uniform charge distribution over the surface of the film under the electrodes. This has made compliant electrodes a key feature of DE actuator technology and the main objective of this paper.

In order to achieve this purpose, an experimental characterization has been carried out with different DE actuators in order to characterize different properties of electrodes. Among important parameters, electrical conductivity and topography of the electrodes were studied under a number of pre-strain levels. Additionally, electromechanical response has been systematically characterized as a function of applied voltage and pre-strain level, and finally a study was performed on the electromechanical response, regarding curing state and different thicknesses of the rubber electrode.

## 2. Experimental

### 2.1 Materials

The study goes with VHB 4910 elastomer since it provides the largest displacements and work outputs of all tested materials so far. Also, this material is commercially available as an adhesive tape which does not require elaborate fabrication. [14] It is a polyacrylic film, very sticky and can be stretched more than 36 times in area. Graphite powder (*4206 Merck*), carbon conductive grease (*Mgchemical 846*), silver conductive grease (*Circuitworks cw7100*) and carbon conductive rubber (*RTV 60-CON*) were chosen as 4 different conductive materials for compliant electrodes.

### 2.2 Actuator fabrication

A piece of VHB4910 was prestretched on a frame, from 15 mm to 100 mm (567% horizontal pre-strain). Plastic triangular plates 100mm long were glued to the film along x-direction and 10mm apart in the y-direction (see Fig. 2). Thin strips of VHB were attached to the film on the edge of the area spanned by the beams in order to keep the area relatively square when the actuator is released from the frame. Then, vertical pre-strain was applied in different levels ranging from 100% to 500% in 50% steps. After stretching, depending on which experiment is aimed to perform (constant strain or strain measurement experiment), electrodes were applied on the central portion or on the entire area of the film as follows; Graphite powder by a soft paintbrush; Grease electrodes, both silver and carbon, by stenciling; and suspended conductive silicone rubber electrode in n-heptane (1/2 w/w) by an air-brush. The actual dimensions of the electrode coated area of the film were 10mm×60mm in the strain measurement geometry (Figure 2-b), while in constant strain; they depended upon the applied prestrain

level. Finally leads were attached and electrical connections between leads and electrodes were ensured using conductive grease.

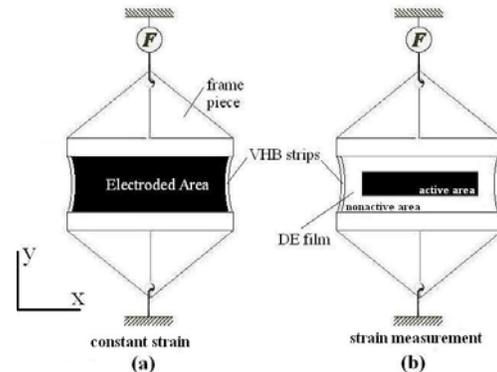


Fig. 2. Actuator design for different experiments (a) constant strain (b) strain measurement.

## 2.3 Measurements

### 2.3.1 Electrical resistance

Electrode resistance measurements were examined on all of the electrode samples in different pre-strain levels. Two-probe method was performed with a digital multimeter (*SANWA PC5000*) in order to measure the resistance of the electrodes. [12] The electrode coated film was stretched with increments of 50% and the resistance was measured between two terminal nodes of the sample at each state of strain. Measurements of surface resistance of semi-solids and powder materials inherently possess a lot of errors and fluctuations. In order to minimize effect of experimental errors a number of 20 experiments were performed in every strain level. Since the precise cross-sectional areas of the electrodes could not be obtained easily; the surface resistance of the electrodes was used for the effectiveness of the electrodes to be compared.

### 2.3.2 Electrode topography

Surface uniformity and mechanical stability under strain are among essential properties of the electrodes which affect the final performance of the actuator. In order to evaluate these properties, topography of the electrodes was investigated through a series of microscopic images. Using an optical microscope, microscopic images of the electrodes under strain were taken with increments of 50%.

### 2.3.3 Actuator electromechanical tests

Two kinds of experiment have been performed for electromechanical response of actuators. Constant strain experiments and strain measurement experiments. Figure 2 shows the geometries of two different experiments. The constant strain experiment is also known as the blocking force experiment. In this experiment, the force generated due to the applied voltage is measured, while the length of

the actuator is fixed. The constant strain experiment has been used to confirm the actuator performance with Maxwell stress theory. [10] In the strain measurement experiment only a particular area of the film is coated by the electrode. As it is shown in Figure 2, in this geometry the actuator consists of two zones, an active zone as the electrode coated area in the center, and a passive zone which surrounds that. After applying voltage, the active zone expands while the passive one contracts so that the actuation strain could be measured by recording the area expansion. The most beneficial feature of this system is measurements of the force and strain parameters, which could be made simultaneously.

An electromechanical measurement system has been used to study the strain response of the actuator alongside the force induced by Maxwell stress effect. As shown in Fig. 3, the actuator was mounted in series with a force gauge. Excitation voltages were applied using a DC high voltage source, ranging from 500V up to 6000V. The area expansion was measured by a digital video camera 1sec after each excitation voltage together with the corresponding force measured by the force gauge.

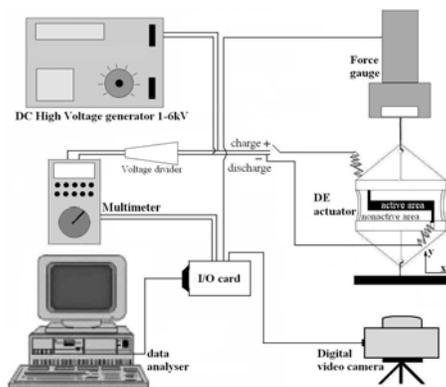


Fig. 3. Experimental setup.

### 3. Results and discussion

#### 3.1 Electrodes' resistance under strain

Toth et al have characterized variation in resistance of several electrodes as a function of strain. They expressed their empirical observation of strain-resistance relationship with the following formula [11]:

$$R = R_0(\beta)^{(\alpha-1)} \quad \text{And} \quad \beta = \frac{R_1}{R_0} \quad (2)$$

Where R is the resistance of the electrode in every strain,  $\alpha$  is the aspect ratio and  $R_1$  and  $R_0$  are the resistances measured at  $\alpha$  equal to 1 and 2 respectively. They also calculated values of  $\beta$  for some common electrode materials. The higher  $\beta$  means the electrode loses more conductivity in the stretched condition.

Table 1.  $\beta$  values for different electrode material [11].

| Electrode material       | $\beta$ value |
|--------------------------|---------------|
| Graphite powder          | 22            |
| Carbon conductive grease | 4             |
| Silver conductive grease | 6.8           |
| Carbon conductive rubber | 6.5           |

Table 1 shows  $\beta$  values obtained for different electrode materials. As it is expected, graphite powder has had the highest influence from stretching, while the other electrodes showed reasonably lower  $\beta$  value in this manner.

Resistance of electrodes under strain alongside their correspondence calculated amount from equation 2, are shown in Figure 4. As it has been expected from the equation, resistance of the electrodes dramatically increases under strain. With the exception of graphite powder, good agreement between experimental data and equation 2 is inferred by other electrodes. In addition, remarkable differences in electrical conductivity of electrode materials should be considered. Superior conductivity of silver particles possibly makes the resistance of silver grease electrode, the best with 3 orders of magnitude less than carbon grease electrode which is in the second grade. The resistance of graphite powder, as the worst one, rose rapidly after applying 50% of pre-strain and it totally became nonconductive around 100% pre-strain. Accordingly, different surface resistance of electrodes will affect actuator performances as it will be discussed later in this article.

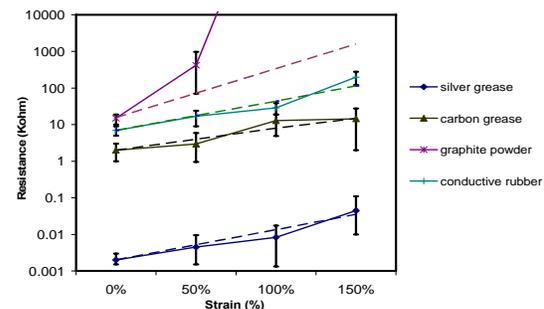
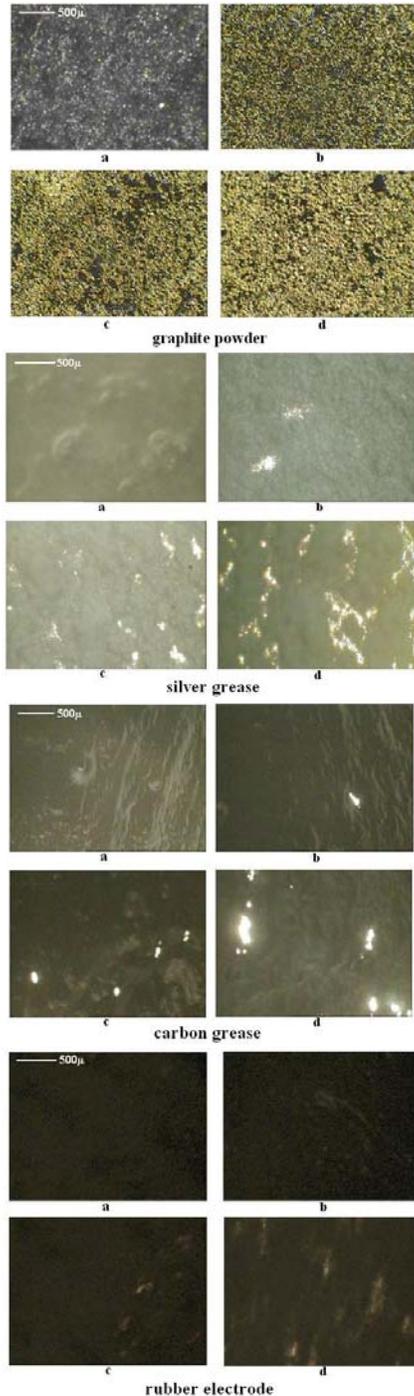


Fig. 4. Behavior of different electrode material under strain (values with error bar) beside correspondence values from equation 2 (dash lines)

#### 3.2 Topography of the electrodes

Optical microscopic images of electrodes under strain are shown in Figure 5. In graphite powder, with increasing strain, an increase in distances between particles could be observed, which is in a good agreement with different behavior of graphite powder obtained from previous section. On the other hand, crack formation was observed in grease electrodes, which could be one of the reasons of the mentioned increase in electrical resistance.

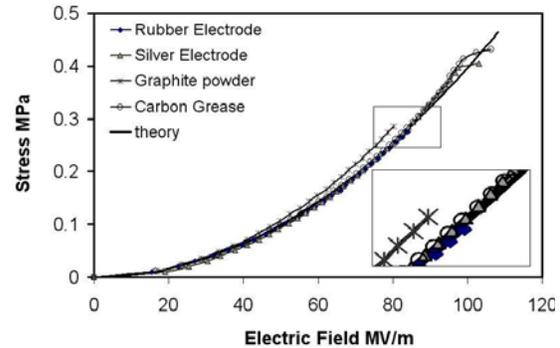


**Fig. 5.** Optical macroscopic images from surface of different electrodes under a) 0% b) 50% c) 100% d) 150% strain.

### 3.3 Constant strain experiment

Constant strain experiments were carried out for actuators with different electrode materials in 567% × 400% pre-strain. Electrical field and corresponding Maxwell stress were calculated from the applied voltage and actuation force divided by dielectric layer thickness, respectively. Thickness was simply obtained from a simple

evaluation using the common formula used for parallel plate capacitors  $z = \epsilon \epsilon_0 A / C$ , where  $C$  is the electrical capacitance of the electrode coated area of the actuator, measured by Multimeter in  $F$ , and  $A$  is the area in  $m^2$ . Kofod et al have investigated dielectric constant of VHB 4910 versus area increase ratio which is equivalent to our applied pre-strain. Based on their observations, a modified dielectric constant ( $\epsilon = 4.485$ ) was used to calculate more accurate thickness amounts.[15]



**Fig. 6.** Maxwell stress vs. Electric field for actuators made of different electrode materials beside theory curve at 567% × 400%.

Results of constant strain experiments are shown in Fig. 6. All of the actuators made of different electrode materials are in a strong agreement with the theory, which is a good confirmation for the method of fabrication and operation setup of the actuators. Fixed dimensions of actuators in this geometry cause the same response for every actuator with respect to theory (Eq. 1).

### 3.4 Strain measurement experiment

The electromechanical response of actuators with different electrode materials was measured. When a voltage difference is applied between the electrodes, the active zone expands while the inactive one contracts (Fig. 7). Removing the applied voltages causes the reverse change. Generated actuation forces and electromechanical strains for each pre-strain and voltage are shown in Figure 8 for the actuator made of silver grease. Both the actuation force and strain always increase as a function of voltage for a given pre-strain, as expected from Equation 1. Moreover, there is an initial increase in these parameters due to pre-strain but a subsequent decrease when larger pre-strains are applied. By increasing the level of pre-strain, the DE film becomes thinner while it causes more molecular orientation of the polymer, which makes it stiffer in the pre-strained direction. The latter pair are counteracting so that they cause an optimum level of pre-strain to achieve the maximum force and strain as indicated in Figure 8. This amount of prestrain was *ca.* 200% and *ca.* 250% for maximum actuation force and electromechanical strain, respectively. The corresponding

dielectric layer thicknesses for the above mentioned prestrains are 90µm and 75µm, likewise. The same behavior was found in other samples made of other electrodes but with different peak values. Finally, one should note that similar behavior between the electromechanical strain and actuation force was observed; which imparts the importance of our loading condition.

Results of actuation force at optimum prestrain level are shown in Figure 9. Actuation force was higher for grease electrodes, because of good compliancy with DE substrate. A saturation effect was observed in high electric fields for graphite powder electrode which causes a premature electromechanical response in the actuator. As it has been illustrated in microscopic images of electrodes' surface, large deformation of the active zone due to lack of a compliant carrier for graphite particles disconnects surface particle connections thus electrode loses its surface conductivity, required for higher actuation.

Electromechanical coupling efficiency is another useful parameter which is defined as "the amount of energy converted into mechanical work per cycle/electrical energy applied per cycle". Pelrine et al estimated coupling efficiency based on the capacitance change of the actuator in terms of thickness strain. Their formula can be rewritten in term of area strain, εA, as follows:[1]

$$k^2 = 1 - 1/(1 + \epsilon_A)^2 \quad (3)$$

Where  $k^2$  is the electromechanical coupling efficiency.

Electromechanical coupling efficiency is influenced by electrodes as an important part of DE actuators. More electrical loss in the electrodes causes less coupling efficiency of the actuator. So this parameter is used as a criterion to compare different electrodes and their performance in our actuators. Table 2 shows maximum coupling efficiency of actuators with different electrodes in optimum loading condition. G. Kofod found the maximum efficiency of 87% for his actuators.[10] It shows that with the exception of graphite powder, other electrodes have had acceptable efficiencies.

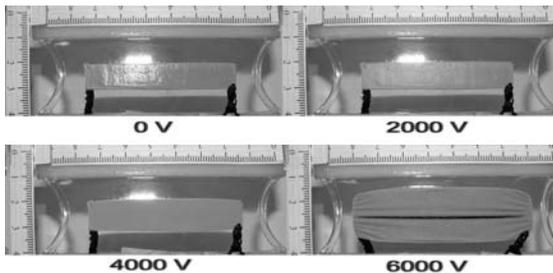


Fig. 7. Actuator response in different operating voltages (silver grease actuator).

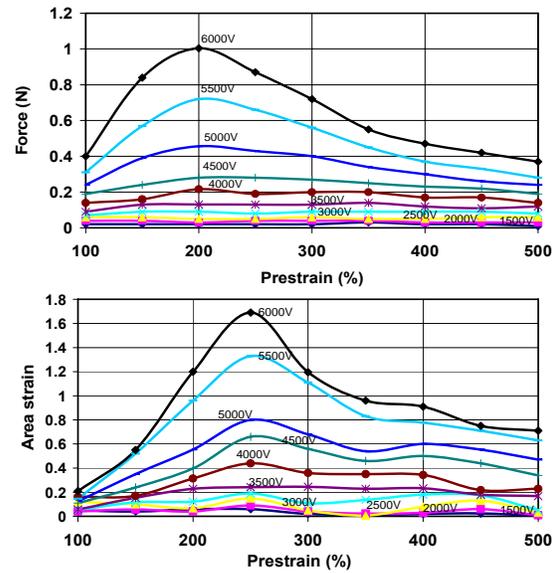


Fig. 8. Electromechanical response of actuator made of silver conductive grease: actuation force vs. pre-strain and voltage (left figure), area strain vs. pre-strain and voltage (right figure).

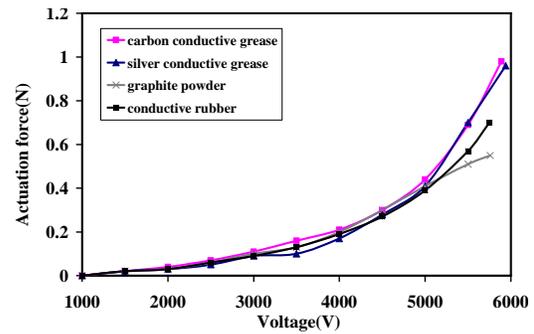


Fig. 9. Actuation force of the actuators in 200% x 567% prestrain.

Table 2. Maximum response of actuators with representative electrodes.

| Electrode material | Electromechanical strain | Coupling efficiency [k <sup>2</sup> ] |
|--------------------|--------------------------|---------------------------------------|
| Silver grease      | 170%                     | 86%                                   |
| Carbon grease      | 160%                     | 85%                                   |
| Conductive rubber  | 156%                     | 84%                                   |
| Graphite powder    | 92%                      | 73%                                   |

### 3.5 Rubber electrode thickness in actuator response

A series of samples were prepared with 3 different rubber electrode thicknesses ( $40\mu\text{m}$ ,  $80\mu\text{m}$ ,  $120\mu\text{m}$ ) in  $200\% \times 567\%$  prestrain in order to characterize effect of rubber electrode thickness on the actuator response. Samples were prepared with the same method as described before in the article. Thickness of the electrodes was measured with a Wet Film Thickness Meter on the rigid frame beside the sample approximately one minute to let solvent evaporates. The  $200\% \times 567\%$  prestrain level was chosen because of the best results of electromechanical response obtained in strain measurement experiments. Figure 10 shows the actuation force provided by these actuators in different driving voltages. By increasing electrode thickness, the actuation force linearly decreases. Voltage constant lines were extrapolated to zero thickness. Table 3 shows the actuation forces of a hypothetical actuator made of rubber electrode at zero thickness, versus corresponding values of the actuator made of carbon grease electrode in the same loading condition.

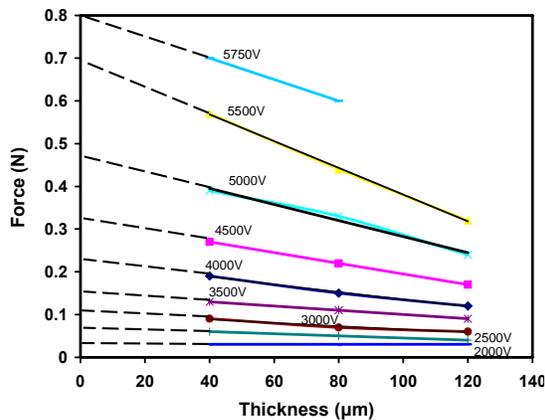


Fig. 10. Actuation force of the actuator made of rubber electrode in different electrode thicknesses ( $200\% \times 567\%$  prestrain).

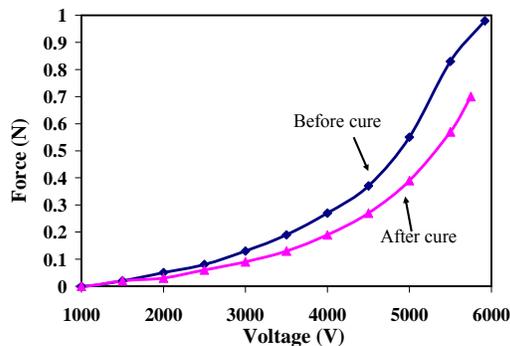


Fig. 11. Actuation force of the actuator made of rubber electrode (thickness:  $40\mu\text{m}$ ) in different curing state ( $200\% \times 567\%$  prestrain)

Table 3. Actuation forces of the actuator made of rubber electrode in zero thickness versus corresponding values of grease electrode.

| Voltage | <sup>a</sup> F <sub>M</sub> (N) | <sup>b</sup> F <sub>C</sub> (N) | Voltage | F <sub>M</sub> (N) | F <sub>C</sub> (N) |
|---------|---------------------------------|---------------------------------|---------|--------------------|--------------------|
| 0       | 0                               | 0                               | 3500    | 0.15               | 0.16               |
| 1000    | 0.00                            | 0.00                            | 4000    | 0.22               | 0.21               |
| 1500    | 0.02                            | 0.02                            | 4500    | 0.32               | 0.30               |
| 2000    | 0.03                            | 0.04                            | 5000    | 0.47               | 0.44               |
| 2500    | 0.07                            | 0.07                            | 5500    | 0.69               | 0.69               |
| 3000    | 0.10                            | 0.11                            |         |                    |                    |

<sup>a</sup>F<sub>M</sub>: Maximum load which an actuator made of rubber electrode could hypothetically have in zero thickness  
<sup>b</sup>F<sub>C</sub>: Actual generated force of the carbon grease actuator

The comparison between these values revealed that how effectively thickness of rubber electrode could influence the actuator response. F<sub>M</sub> and F<sub>C</sub> values are quite the same in every excitation voltage. Although rubber electrode shows more mechanical stability than grease electrode (i.e. the lowest crack formation on the surface), its thickness should be definitely controlled in a way that minimum mechanical constrain is imposed on the actuation response.

Fig. 11 shows the actuator response in terms of actuation force for different curing states. A decrease in response of cured sample is observed in respect to non-cured one. Increasing the elastic modulus of the electrode due to chemical crosslinks between silicone chains leads to some mechanical constrains for the dielectric layer and subsequently lowers the ultimate response. Although rubber electrodes may imply some restrain for actuation, owing to their cleanness and workability after cure, they are introduced as a practical approach to make compliant electrodes. Yet, the distribution of conductive particles in the elastomeric matrix should be maintained during curing process.

## 4. Conclusions

Effect of different electrode materials on the performance of DE actuators was investigated. The electromechanical response of DE actuators strongly depends on the electrode material and pre-strain levels. There is an optimum level of prestrain in which the maximum response is attained. Different electrodes showed different surface stabilities which led to particle divergence in graphite powder and crack formation in grease electrodes. These phenomena affect actuator's dissimilar performances which could be explained in terms of different amount of effective electric field generated on the surface of different electrodes at high deformations. More instability on the surface as well as higher surface resistance of electrodes weakens effective electric field and reduces actuator performance. The response of the actuator made of graphite particles shows that existence of a polymer carrier for conductive particles is in imperative demand, particularly when large deformation is required.

On the other hand silver electrode showed the best result, although conductive rubber is more convenient for actuator applications. In the applied condition and materials, the thickness of rubber electrode should be necessarily less than dielectric layer thickness to eliminate the effect of mechanical constraints and achieve higher response.

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