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Dielectric Elastomer based active layer for macro-scaled industrial application in roto-flexographic printing

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ABSTRACT

The use of dielectric elastomer (DE) for the realisation of new generation actuators has attracted the interest of many researchers in the last ten years due to their high efficiency, a very good electromechanical coupling and large achievable strains [1-3]. Although these properties constitute a very important advantage, the industrial exploitation of such systems is hindered by the high voltages required for the actuation [4] that could potentially constitute also a risk for the operators.

In this work we present a DE based active layer that can be used in different macro-scaled parts of industrial equipment for roto-flexographic printing substituting traditional mechanical devices, reducing manufacturing costs and enhancing its reliability. Moreover, the specific configuration of the system requires the driving voltage to be applied only in the mounting/dismounting step thus lowering further the operative costs without posing any threat for the workers.
Starting from the industrial requirements, a complete thermo-mechanical characterisation using DSC and DMA was undertaken on acrylic elastomer films in order to investigate their behaviour under the operative frequencies and solicitations. Validation of the active layer was experimentally evaluated by manufacturing a DE actuator controlling both prestrain and nature of the complaint electrodes, and measuring the electrically induced Maxwell strain using a laser vibrometer to evaluate the relative displacement along the z-axis.

1. INTRODUCTION

Dielectric elastomer (DE) based actuators are part of the largest family of the so-called "electroactive polymer devices" and made their first appearance in the second half of the nineties as adaptive structures [5]. Because this kind of devices can be modelled as compliant capacitors, when they are exposed to an external electric field positive charges will appear on one surface while negative charges will be placed on the other. The presence of opposite charges on the capacitor leads to Coulomb attraction forces thus generating an internal pressure known as Maxwell stress that is able to squeeze the sample. Because these materials are considered incompressible, the reduction along the thickness z is accompanied by an increase along the two planar directions x and y. Although this mechanism requires high input voltages (in the range of 1-10 kV), the very large strains available to this actuators together with the relative manufacturing simplicity have attracted the attentions of several researchers who investigated their use in robotic applications [6, 7].
The aim of this work is to experimentally evaluate the use of dielectric elastomer based actuator to develop adaptive structures for macro-scaled industrial applications, in particular for printing industries. Indeed, because of the high levels of achievable displacement, the use of electroactive shape-morphing layers could substitute traditional mechanical connections between rigid parts, reducing the complexity of the manufacturing process. However, as industrial working environments requires the material to be able to resist at particular working conditions (in terms of frequency, temperature and electrical inputs) a complete characterization of the material to be used for the actuator manufacturing must be undertaken. Moreover, as different manufacturing variables such as initial prestrain, electrode material, electrical connection requirements and superficial constrain play a fundamental role in the design of such devices, all these aspects have been investigated and experimentally validated.

2. ACRYLIC FILMS CHARACTERIZATION

Because of the very good results obtained by previous authors, the chosen material for the realisation of the adaptive structures is the acrylic elastomer VHB 4910 produced by 3M Company. The properties of the VHB 4910 have investigated by several authors especially from an electrical point of view, analysing the dependence of the electrical constant over a large range of frequencies. Analysing the results of a series of experimental tests, Jean-Mistral et al stated that changes in the dielectric constant recorded versus frequency and temperature are caused by the presence of polar

groups on the side chains of this elastomer that induce a sub Tg transition (β-relaxation)[8]. Moreover, they investigated the strong dependence between the dielectric constant and the nature of the electrode, recording a value of 4.7 for gold electrodes that increased up to 5.4 when conductive silver grease is used. Other authors have investigated the frequency dependence of polyacrylics [9], however very few works have been aimed to the dependence between temperature and mechanical properties of such materials.

In order to validate the choice of VHB 4910 as dielectric elastomer for the manufacturing of an adaptive layer several tests were carried out aimed to the characterisation of the material. Thermal properties have been evaluated using a Differential Scanning Calorimetry (DSC) equipment. Samples of 5 mg were initially heated up to 90 degrees at a rate of 5 °C per minute and held for 10 min at this temperature in order to remove all the thermal history. Subsequently, the temperature was lowered down to -80 °C at a rate of 5 °C.
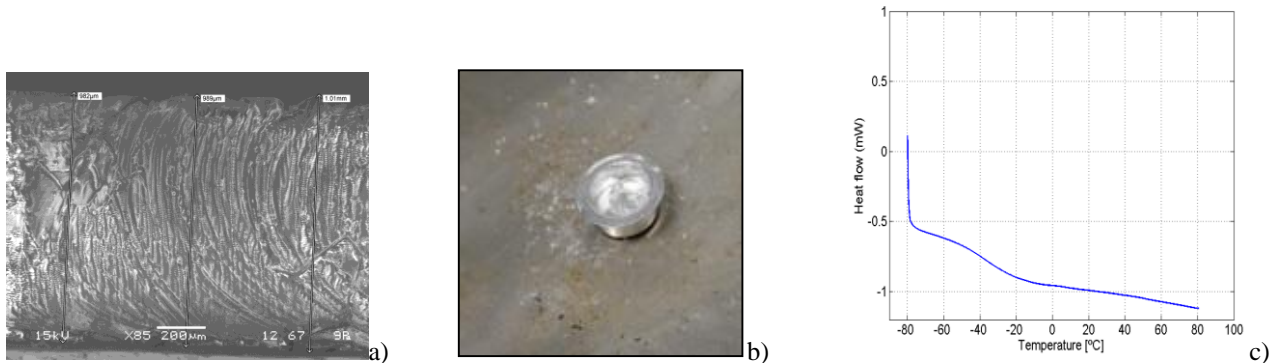

Figure 1 - a) SEM image of the cross section of a VHB 4910 film, b) DSC crucible filled with 5mg of elastomer; c) DSC thermogram of the VHB 4910

The results of the DSC analysis are represented in Figure 2c, where it is possible to observe a broad glass transition positioned at -40 °C. Since the operating temperatures of the industrial machines for flexographic printing are in the range between 20 and 50 °C, it is important to ensure the absence of any phase transition in this interval. As is possible to see from the image, no secondary transitions are present in the temperature working range. Similar results have been obtained by other authors and are present in literature [10].

As for the mechanical behaviour, Dynamic Mechanical Analysis (DMA) was performed in order to evaluate how the working temperatures can affect the mechanical properties of the material such as rigidity and damping. Samples 10x5x1mm were tested in tensile mode at a frequency of 1 Hz in a temperature range between -20 and 80 °C with a ramp of 2 °C per minute.

Storage Modulus can be interpreted as a representation of the elastic behaviour of a material when it is subjected to an external load, therefore it is ideally related to Young's Modulus, showing a similar behaviour with temperature. However, since these quantities are related to distinct material charateristics, their numerical values will be different. Another important physical parameter that is possible to determine with a DMA test, is the damping factor (or tan δ), which can be defined as the ratio between the loss modulus (E'') and the storage modulus (E') and represents a measure of the amplitude reduction of an oscillatory system due to energy absorption mechanisms. This value is equal to zero for an ideal elastic material, whilst for an ideal viscoelastic material it is infinitive.
The behaviour of the storage modulus versus the temperature is represented in Fig 2a, together with the loss modulus. As it is possible to observe from the picture, the VHB 4910 shows the typical temperature-depending behaviour of an amorphous polymer, showing a decrease of almost three orders of magnitude during the glass transition for the storage modulus (from 100 to 0.1 MPa). As for the DSC analysis, also for the storage modulus is important to observe that there are no significant variations within the temperature range of industrial printing devices, as very small differences are observed in the temperature gap between 20 and 50 °C and there is no presence of secondary transitions.
Fig 2b shows tan delta as a function of temperature at a frequency of 1 Hz. The same broad glass transition can be observed also from the behaviour of tan delta, showing a strong increase in its value from -20 to 10°C (from 0.4 to 0.95) and a decrease from this peak to 80 °C (down to 0.25).

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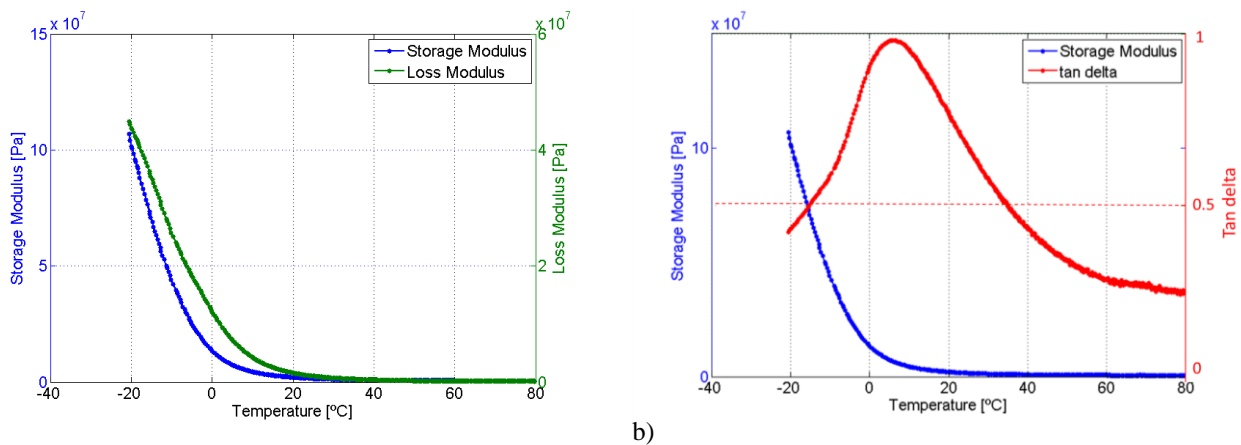
a)   b)

Figure 2 - Storage and Loss moduli behaviour with temperature for VHB 4910; Tan delta behaviour with temperature for VHB 4910

As said in the introduction, the characteristics of a DE based actuator are strongly influenced by the operating frequencies. This is due to the possible presence of structural changes that could happen within the structure of the material, modifying its physical properties thus affecting its mechanical stability. As a consequence, it is very important to investigate how the acrylic material will react as its working frequency increases within the operative range.

Traditional commercially available flexographic printing unit are characterised by a printing velocity (v_m) in the range between 10 and 70 meters per second. Therefore, considering an increasing diameter of the printing units from 10cm to 60cm, it is possible to easily estimate the frequency of solicitations acting on a layer of dielectric elastomer that rotates together with the printing unit, by using the equation $f = v_m/60(d\pi)$. As it is possible to observe in Fig 3, the working frequencies are mostly in the range between 0.5 and 4.7 Hz, showing a direct proportionality with the printing velocity and an inverse relationship with the device diameter.
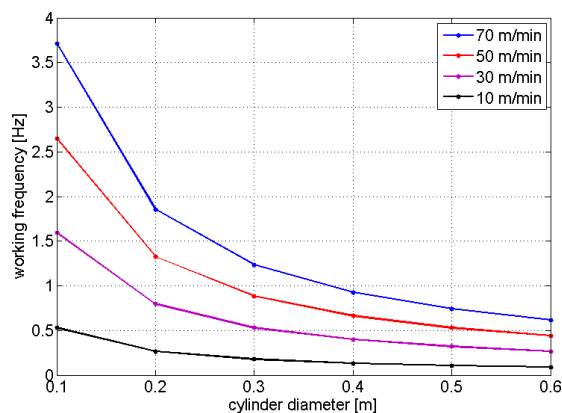

Figure 3 - Working frequency as a function of printing cylinder diameter

Based on these considerations, the behaviour of storage modulus and tan delta in the range between 0.01 and 40 Hz has been investigated for VHB 4910 using the same experimental setup in the DMA instrument, and the results are illustrated in Fig 4.

As it is possible to see from the images, storage modulus increases with increasing frequency, going from 0.4 to 3.9 MPa, while tan delta reaches a peak of 1.1 in correspondence of 38.5 Hz and then decreases by 10% at 40 Hz.

The dependence of the storage modulus (that represents the elastic behaviour of a polymer) from the frequency represents an important factor for the feasibility analysis of dielectric elastomer actuators as it will determine the behaviour of the polymer during the working cycle. In particular, the increase in the storage modulus with increasing

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frequencies can constitute a beneficial effect for this kind of applications, meaning that during the working cycle the polymeric layer will increase its stiffness, enhancing its stability by lowering the presence of mechanical instabilities due to structural vibrations.
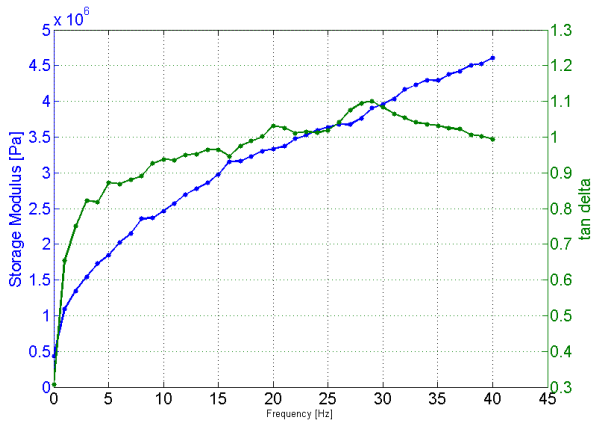

Figure 4 - Frequency dependence of storage modulus and tan delta at 30 ºC

Moreover, considering that tan delta represents the internal friction of the viscoelastic system, it is possible to analyse the efficiency of a dielectric elastomer actuator as a function of both temperature and frequency by observing the behavior of the mechanical damping, following the same approached used by Sheng et al [11]. This is due to the proportionality between the total efficiency of an actuator (η_t) and its mechanical efficiency (η_m) which is strongly affected by the viscoelastic property.

In other words, it is possible to determine the mechanical efficiency of an elastomer by using the following equation [12]:
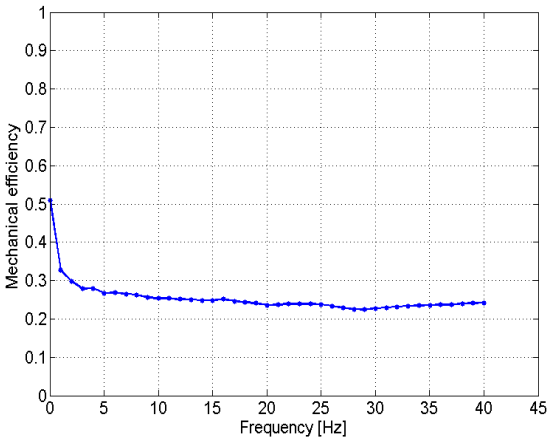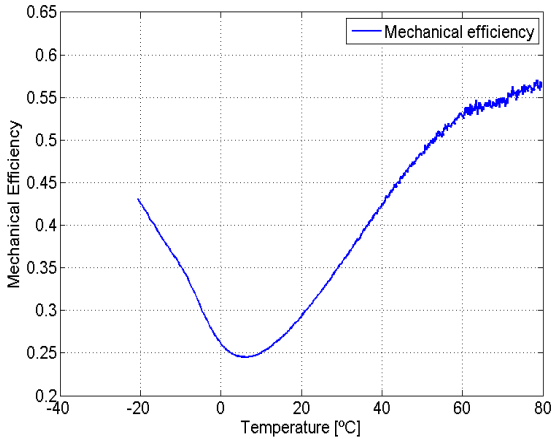
$$\eta_m = \frac{1}{1 + \pi(tan\delta)}$$

a)   b)

Figure 5 - Mechanical Efficiency of VHB 4910: a) dependence with temperature; b) dependence with frequency

As it is possible to observe from the Fig 5, mechanical efficiency shows a very rapid decrease when the temperature is increased from -20 to 7 ºC, going from 0.45 to 0.25% (Figure 5a). Increasing the temperature from 7 to 80 degrees leads to an increase of the mechanical efficiency, going from 0.25 to almost 60%.

As for the frequency dependence, the increase in mechanical damping leads to a small decrease (less than 15%) of the mechanical efficiency for very low frequencies with a relative secondary peak at 4 Hz. However, in the analysed range increasing the working frequency up to 40 Hz leads to a monotonous decrease of the efficiency by only 4%.

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In conclusion, the thermo-mechanical analysis of the VHB 4910 acrylic elastomer has shown a strong dependence of the mechanical properties on both frequency and temperature. This behaviour implies that particular attention must be given to the system requirements prior to the choice of the specific material for the realisation of the actuator. Indeed, in case of the VHB 4910 the relatively small temperature range required (from 0 to 50 °C) and the low frequencies (below 10-15 Hz) connected with the flexographic printing procedure make this material a good candidate for the realisation of adaptive structures.

The employment of this acrylic elastomer for low frequencies applications due to the increase in mechanical efficiency for low frequencies was already suggested by other authors [9]. Moreover, the increase of the storage modulus for low frequencies can be exploited to improve the mechanical properties of the active layer reducing any mechanical discontinuity.

3. EXPERIMENTAL SETUP

As the principal aim of this work is to investigate the use of dielectric elastomer based actuators for the realisation of adaptive layers to be used for industrial applications, a specific setup has been designed in order to record the relationship between the input voltage and striction along the z-axis. Fig 6 illustrates the experimental setup used for the test campaign. A dual power supply is used to power a DC/HV-DC converter which is used to feed the DE actuator with a high voltage current ranged between 1 and 5kV. It is important to underline that, although the voltages used to operate these actuators are very high, the current amperage is very low as the converter receives in input only currents from 1 to 15 V. As a consequence, the power requirements of these devices can be kept relatively low. In order to ensure the safety of the experiment avoiding electrical shocks, the sample is placed within a Perspex cage, while data regarding the displacement along the thickness direction, have been collected by a laser vibrometer (see Fig 5c).
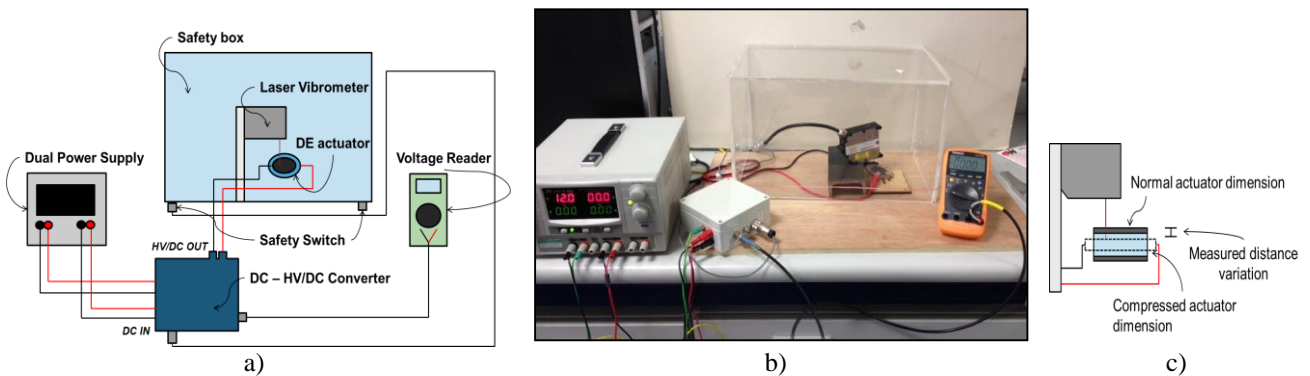

a)   b)   c)

Figure 6 – a) schematics of the experimental setup; b) real system; c) laser vibrometer displacement evaluation setup

4. ACTUATOR PERFORMANCE

During the experimental campaign of this project a large number of samples have been manufactured in order to investigate separately the different variables that play important roles in the realisation of dielectric elastomer actuators.

4.1 Pre-strain effect

In particular, the first series of samples was produced to understand the effect of the prestretch on the performances of the actuator in terms of electro-striction along the thickness. Circular samples of VHB4910 have been stretched along the xy plane using a flexible metal hose until deformation of 100%, 200% and 300% of the initial superficial area were obtained. Active areas of the polymer were delimitated with a PTFE masking and coated with the electrodes by smearing carbon black powder (Cabot) using a neoprene stamp and were linked to the power supply via copper connections.

Image 7a shows the variation of the extent of the active area along the xy-plane when the sample is subjected to a high voltage current. As the polymer volume does not change during the actuation, this superficial deformation is accompanied by a reduction of the thickness along the z-axis.

In terms of industrial exploitation, it is important to measure the geometrical response along the thickness direction when the actuator is subjected to on/off cycles instead of a gradually increasing input voltage. Image 7b represents the cyclic response recorded from one of the actuator and clearly indicates that the material reacts immediately to the applied voltage by showing a constant z displacement for each actuation cycle. Moreover the relaxation of the material is fast enough to guarantee a complete recovery of the initial thickness as soon as the voltage is removed from the surfaces.
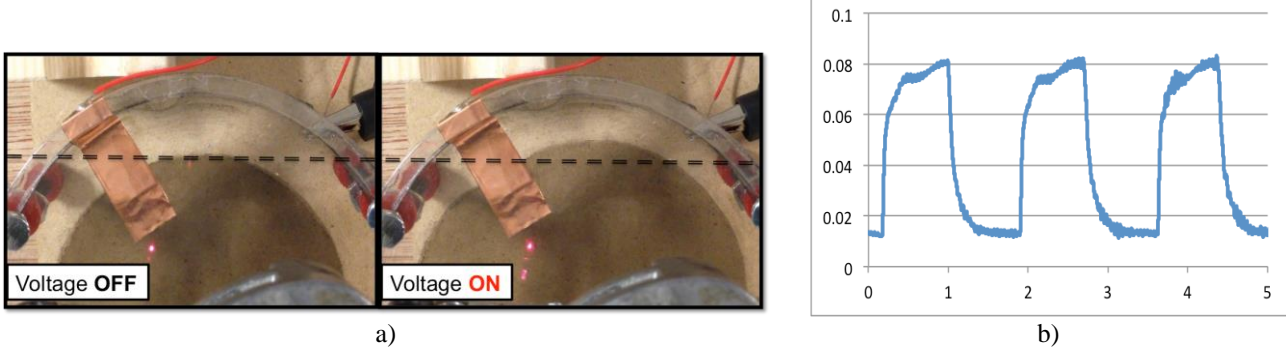

a)   b)

Figure 7 - Increase of the planar surface of the actuator due to electrostriction; b) striction stability to consecutive actuation cycles

The data recorded from the A samples are summarised in figure 8a, which represents the relationship between vertical displacement and voltage. As it is possible to see from the trends, the effect of the prestretch is quite evident, as the 300% sample is able to reach larger displacement than the other samples. This result can be explained analyzing the expression of the Maxwell stress, as indicated from Pelrine et al [5]. The electrostatic energy U that is stored in a film with opposite charges Q and −Q placed on its surface can be written as:

$$U = \frac{0.5Q^2}{C} = \frac{1}{2}\frac{Q^2 z}{\varepsilon_0 \varepsilon A} \qquad (1)$$

Where $C = \frac{\varepsilon_0 \varepsilon A}{z}$ is the capacitance, ε_0 represents the free-space permittivity (8.85x10^{-12}Fm^{-1}) and ε is the relative dielectric constant. The change in stored electrostatic energy dU for a change dz along the z-axis and dA in area can be expressed as:

$$dU = \left(\frac{1}{2}\frac{Q^2}{\varepsilon_0 \varepsilon A}\right) dz - \left(\frac{1}{2}\frac{Q^2 z}{\varepsilon_0 \varepsilon A}\right)\frac{dA}{A} \qquad (2)$$

From the incompressibility of the polymer it is possible to write that $\frac{dA}{A} = -\frac{dz}{z}$, therefore equation above becomes:

$$dU = \left(\frac{Q^2}{\varepsilon_0 \varepsilon A}\right) dz \qquad (3)$$

Considering the definition of the pressure p on the actuator as the change in electrostatic energy per unit area per unit displacement of the film along the z-axis, it is possible to write:

$$p = \frac{\left(\frac{1}{A}\right)dU}{dz} = \frac{\left(\frac{1}{A}\right)\left(\frac{Q^2}{\varepsilon_0 \varepsilon A}\right)dz}{dz} = \frac{Q^2}{\varepsilon_0 \varepsilon A^2} \qquad (4)$$

The electric field E is given by $E = \frac{V}{z} = \frac{Q}{Cz} = \frac{Q}{\varepsilon_0 \varepsilon A}$, therefore the expression of the pressure can be expressed as:

$$p = \left(\frac{V}{z}\right)^2 \varepsilon_0 \varepsilon \qquad (5)$$

As it is possible to observe from the equation above, there is an inverse quadratic relation between the Maxwell stress and the thickness of the actuator. Considering that the same material is used from the different samples, this means that the striction along the z-axis will be higher for films characterised by lower values of the initial thickness z, or that, in the same way, in order to reach particular displacement values, the input voltage requirements will be lower for prestretched samples.

However, prestraining the samples holds also some disadvantages when industrial applications are the primary objective, which are connected intrinsically with the stretching operation. Indeed, Munch et al demonstrated that when a polymer is stretched along the xy directions, the macroscopic chains will be oriented, therefore as they will follow more difficultly the electric field, the permittivity of the material will decrease and the actuator performance is lowered [13]. Moreover reducing the thickness of the active layer can easily lead to the formations of micro-cracks especially in correspondence with the edges of the active area which are physically connected to the power supply. The presence of this kind of damages lowers the mechanical properties of the material locally, increasing the possibility of contacts between the two electrodes, thus limiting largely the maximum voltage that the actuator can sustain, as expressed in Fig. 8b.
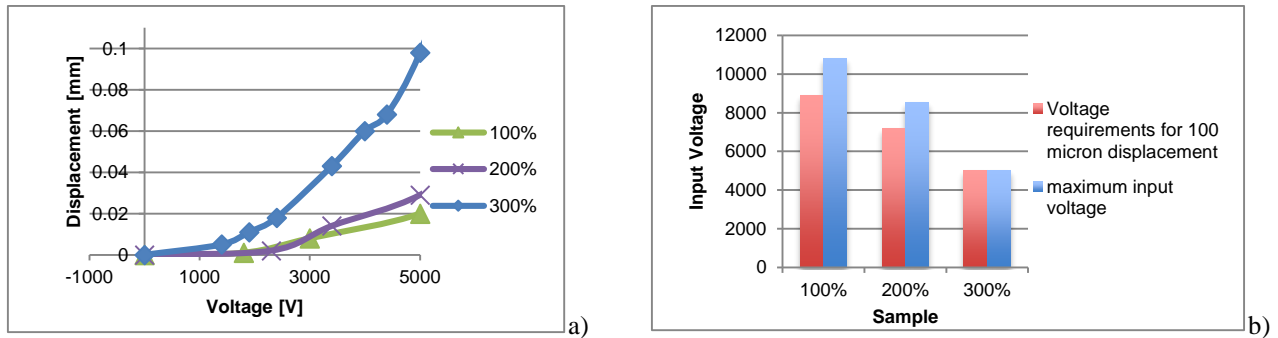

Figure 8 - a) Voltage/displacement relationship of actuators characterised by different extent of the initial prestrain; b) voltage requirements and maximum input voltage for different extents of the initial prestrain

4.2 Compliant electrodes

As reported in many previous works, the nature of the electrodes plays a fundamental role in the efficiency of dielectric elastomer based actuators. Indeed, as the polymeric layer changes its shape due to the Maxwell's stress, the electrodes must maintain their compliance by following this deformation without being peeled off from the substrate. In other words, because of the flexibility of the electrodes, the repulsion of like charges on the same electrode generates a tensile stress in the length and width directions, while the attraction of unlike charges on opposite electrodes generates a compressive stress in the thickness direction. The tensile effect on the xy-plane is ignored in traditional parallel-plate capacitors because the presence of rigid electrodes prevents any conversion of electrical to mechanical energy by stretching. As a consequence, if the electrode does not follow the elastomer during its deformation, the actuation force of the device dramatically decreases.

Based on these assumptions, carbon powder based electrodes have been identified by several authors as a good choice in terms of simplicity and effectiveness. Indeed, of the advantages of using the VHB series elastomers is that being highly adhesive, they strongly simplify the electroding process, enabling the possibility to use carbon black or other "dust" methods without using glues or other reagents. However, although good adhesion between the electrodes and the elastomer is guaranteed, it is difficult to obtain a constant thickness conductive layer (especially when multi-layered structures such as stacked actuators are needed), therefore along with the powder electrodes, other materials have been analysed and experimentally validated during this work.

An important research work focused on the importance of the compliance and on the different available typologies of actuators is contained in the work by Carpi et al [14]. Results from an experimental campaign proved that, despite the good levels of compliance that can be achieved, the electrodes will never work as a perfect conductor. As a consequence, the effective electric field will be different from the ideal one (equals to V/z0 where V is the applied voltage and z0 is the initial thickness of the elastomer) and it can be evaluated from the Gauss' law on an imaginary closed surface that includes one of the electrodes as directly proportional to the charged stored per unit area. As for the actuator performances, for low pre-strain extents and when low electric fields are necessary, the authors reported that the best results were given in terms of electromechanical coupling by thick electrolyte solutions, while for pre-strains above 30kPa, graphite spray electrodes represents an optimal trade-off between simplicity and performances. In a latter paper, the same authors also investigated another procedure based on the doping of a traditional silicone with carbon nanoparticles, obtaining good results in terms of compliance on silicone actuators [15]. Pelrine et al proposed a different approach that is based on the deposition of a ultra-thin gold layers obtained by sputtering [3]. Although high levels of

purity and good conductivity can be achieved by following this methodology, gold electrodes suffer from the big disadvantage to start cracking after 4-5% of elongation. To solve
 this problem, the authors developed a different design, in which gold zigzag patterns are sputtered via photolithography so that they can accommodate larger deformations.
A further evolution of these systems consists in using electrodes that comprises two different conductivities, called also "structured electrodes" in which high conductivity metal traces are patterned on the surface of a low conductivity compliant electrode that limits the breakdown effect, preventing catastrophic failures.

In order to analyse the compliance of different electrode materials, Scanning Electronic Microscope analysis have been carried out on several samples. The analysed coatings were: *Conductive Silver paint*, *Conductive Carbon ink* and *Conductive graphitic spray*. Tests were carried out following two different approaches aimed to simulate the working conditions of the actuators: in the first one, the sample was first coated and then a 300% stretch was applied, while for the second one, they were first stretched by the same extent and then coated. All the samples were characterised by the same dimensions and were stretched together using a specifically designed holder.

Figure 9 - SEM analysis: a) stretching apparatus; b) samples tested during the analysis

As it is possible to observe from pictures 10a and b, silver ink coating does not guarantee the minimum level of compliance required for dielectric elastomer manufacturing, showing areas with large chunks of silver and completely uncoated areas. For pre-stretched samples (Fig 10c and d), the silver coating presents better results, being able to create a continuous layer on polymer, although some large cracks can be seen on its surface that could create discontinuities when the actuators are enabled during several working cycles.
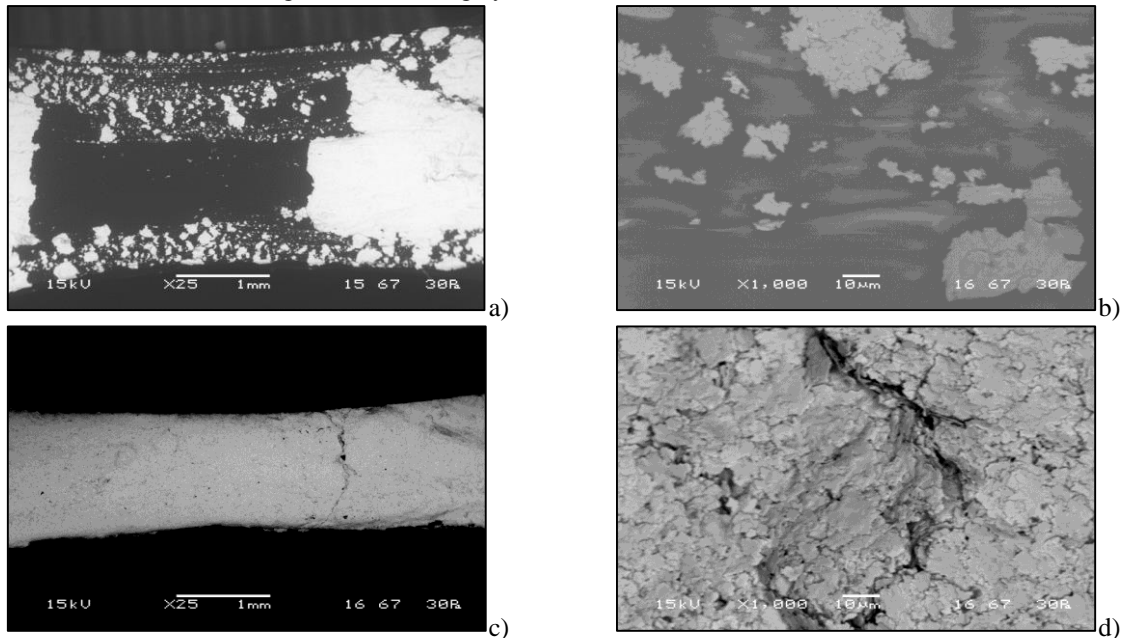

Figure 10 - SEM analysis on Silver ink coated samples: a,b) samples painted before the elongation; c,d) pre-stretched samples
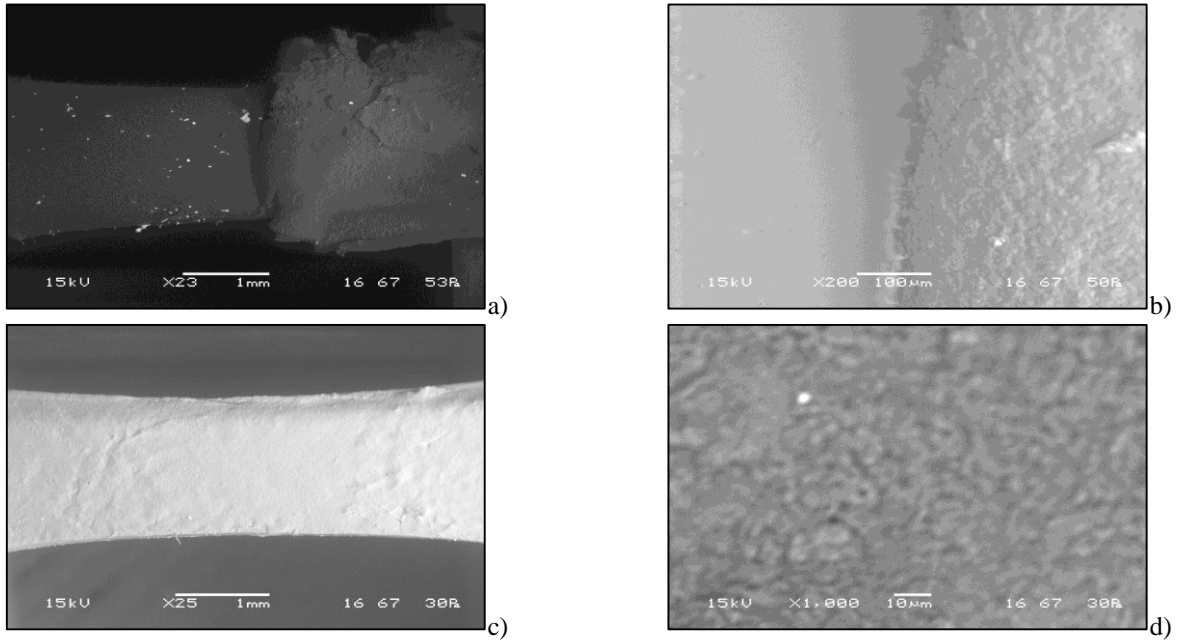
Figure 11 - SEM analysis on Carbon ink coated samples: a,b) samples painted before the elongation; c,d) pre-stretched samples

Results from the analysis on carbon ink are summarised in Fig 11 from which it is possible to observe the large differences between the samples coated and then stretched (Fig 11a and b) and the pre-strained and then coated ones (Fig 11c and d). In fact, as it is possible to observe from Figure 10a and b, when coated samples are stretched, the carbon ink layer is completely peeled out from the polymer, while when the samples are first pre-strained they present a quite smooth continuous surface.
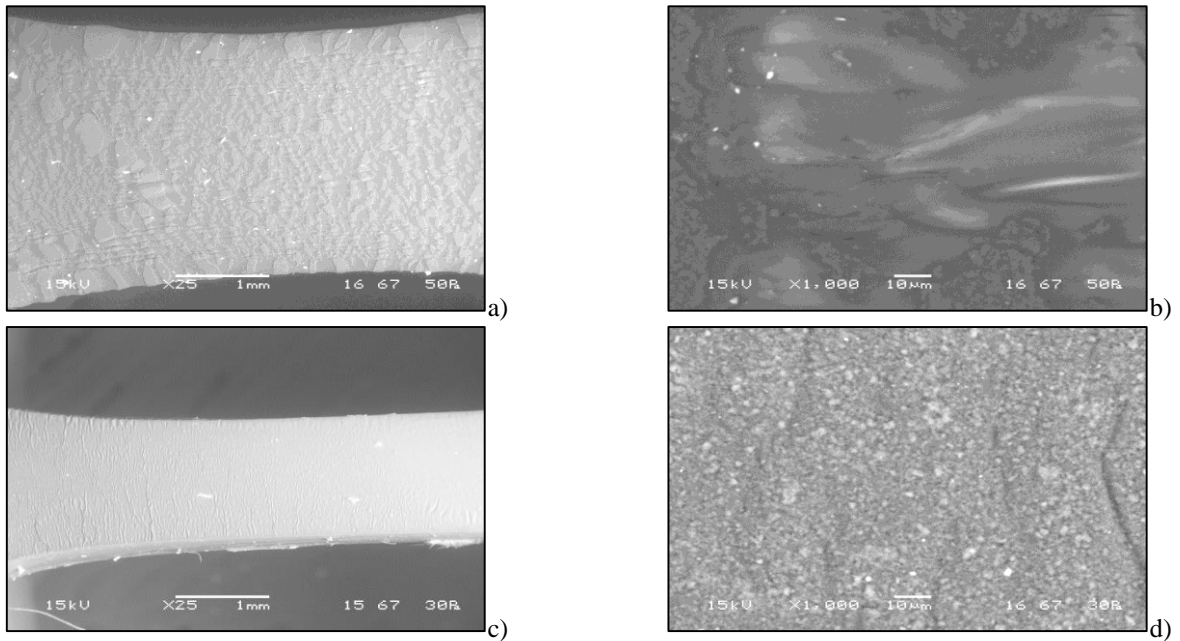

Figure 12 - SEM analysis on Carbon spray coated samples: a,b) samples painted before the elongation; c,d) pre-stretched samples

The results obtained for sprayed samples are shown in Fig 12, from which it is possible to conclude that spray coating gives the best results in terms of compliance and continuity of the electrodes. In particular, samples first coated and then stretched (Figure 12a and b) still present some cracks propagating on the surface, however, if compared with the other two coating material tested, they can guarantee a certain compliance. On the other hand, when the material is pre-strained, the surface of the polymer presents a very good coating, characterised by a fined distribution of carbon particles that creates a continuous smooth layer.
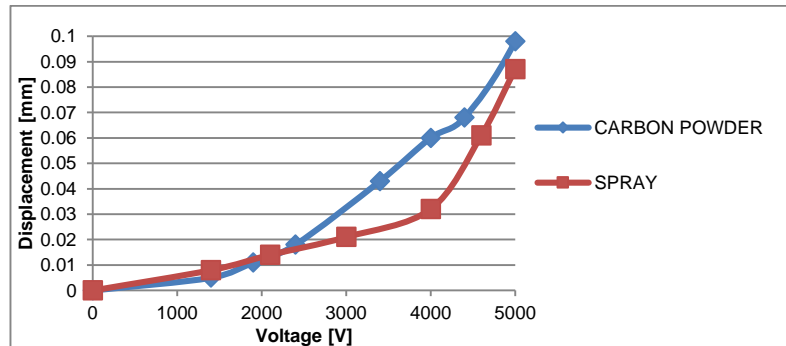

Figure 13 - Comparison between the actuation performance of actuators using carbon powder and graphitic spray as electrode material

Figure 13 represents the voltage/displacement relationship for two different actuators subjected to the same prestrain and coated with carbon powder and graphite spray. As it is possible to see from the image, the performance of the two devices is very similar, proving the effectiveness of the graphite spray electrodes. Moreover, as the coating process is much easier and cleaner (dust electrodes could lead to electrical malfunctions as the powder penetrates easily in any electronic devices such as the DC-HVDC convertor) it represents a valid choice for industrial devices and automatic production lines.

4.3 Substrate Constrain

The use of dielectric elastomers as adaptive structures is strongly bound with their possibility of being installed on other structural parts without losing too much of their morphing ability. Indeed, while the actuators illustrated above were free to expand in the xy-plane, in case of real industrial applications, at least one of the surfaces must be in contact with a rigid substrate that will limit its movements, decreasing the actuator performance. Indeed, as explained in depth by Kofod [16], the presence of a superficial constrain on the passive areas is able to affect the deformation matrix of the material and its tensor stress, leading to an apparent increase of the elasticity modulus of the entire material that hinders the actuator mobility.
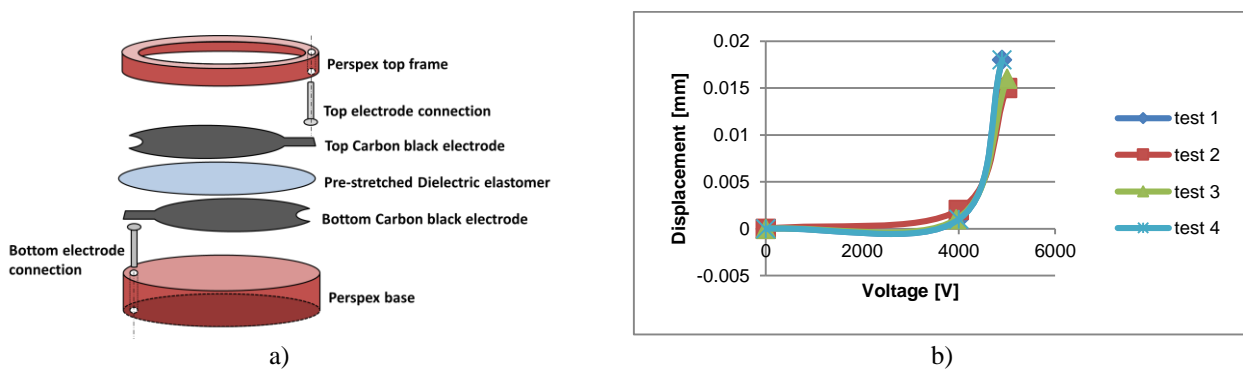

a)   b)
Figure 14 - a) sample B manufacturing layout; b) results of actuation test on sample B

Stacking several layers of DE could solve this problem, as previously demonstrated by Kovacs [17] and Carpi [18], however for those application in which the total thickness of the device represents a key factor, this configuration is not available and other solution must be investigated.

In order to verify the effect of the presence of a rigid substrate, a sample (labeled sample B) was manufactured, by layering a 300% prestrained acrylic film on a Perspex base and framing it with an annulus in order to guarantee a good electrical connection with the power supply (Fig 14a).

The results represented in Fig 14b, showed that the superficial constrain decreases the displacement along the z-axis by almost than 85% (17 versus 100 microns) if compared with the free-standing actuator. In addition because of the friction on the Perspex substrate, there is a certain threshold of almost 4000V below which the actuators movements are completely hindered.

In order to improve the displacement along the z-axis for this actuator a more complex sample (labeled sample C) was prepared. In this case the acrylic layer is held down by a metal tubular annulus in a "button" shape on a 5mm silicone rubber layer which is, in turn, attached on the rigid substrate (Fig 15a). The active area of the acrylic is in contact with the silicone rubber, while the passive area is on its sides. The presence of the silicone rubber layer allows the material to decrease the effect of the superficial constraining allowing larger deformations and reducing the threshold generated by the superficial friction (Fig 15b). A comparison between the two different constrained configurations together with the free-standing actuator is represented in Fig 15c. As it is possible to observe from the data, the button like configuration allows deformations that are almost doubled if compared with the sample B (from 17 to 29 microns), however the presence itself of a substrate still leads to a decrease of 70% in the actuator performance when compared to free standing samples.
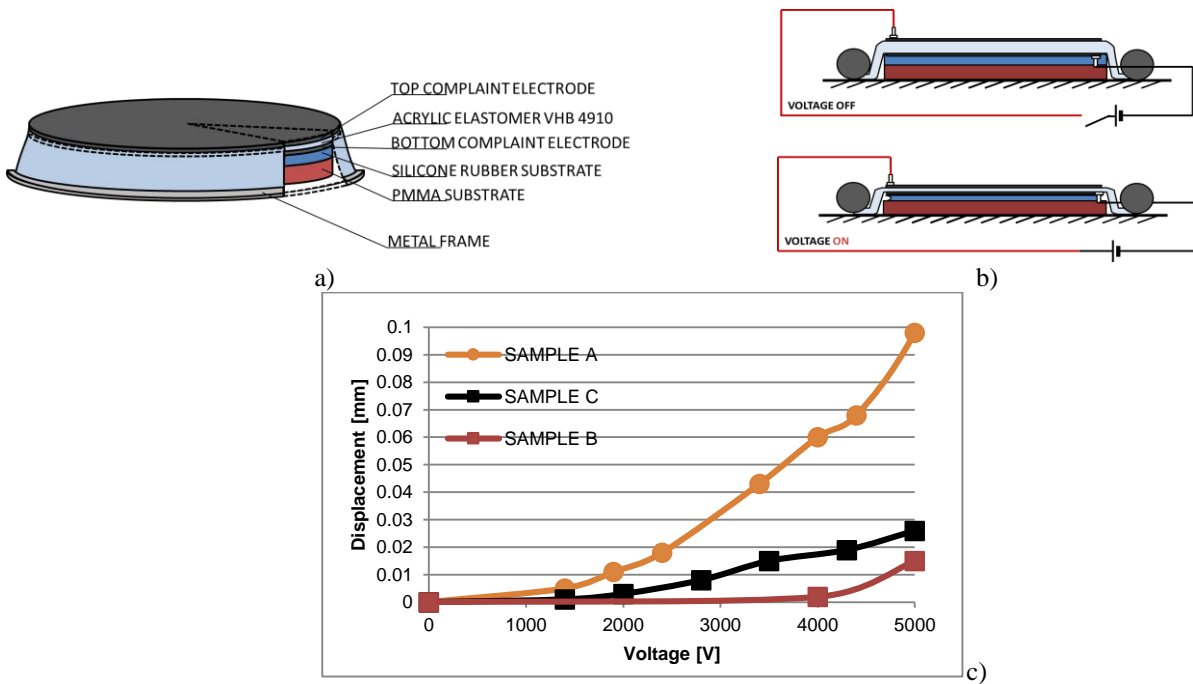

Figure 15 -a) sample C manufacturing layout; b) actuation mechanism behaviour; c) comparison between samples A, B and C

5. CONCLUSIONS

The possibility of employing dielectric elastomer based actuator as adaptive structures for industrial applications was evaluated. In particular, active layers able to respond to an applied voltage by reducing their thickness could constitute a valid alternative to traditional locking system for flexographic printing devices. Because of the large numbers of works present in literature, VHB 4910 acrylic elastomer was chosen as dielectric polymer and subjected to a complete thermo-mechanical analysis. Results from DSC and DMA proved that there is no presence of any transition in the working temperature range of traditional printing devices. Moreover, the acrylic responds to an increase in the working frequency

by increasing its storage modulus by one order of magnitude, enhancing its mechanical performance thus reducing the amplitude of mechanical instabilities due to structural vibrations. The effect of the prestrain was also investigated by manufacturing different actuators with film subjected to different prestretch rate, showing a direct relationship between the electrostriction and the initial thickness of the polymer film. However, as the material is stretched it becomes more fragile and susceptible to microcracks and damages that could largely limit their industrial applications. The nature of the electrodes was also analysed in order to find a "cleaner" and easier alternative to powder based electrodes by carrying out SEM analyses on different electrodes materials. Results from this investigation indicated that graphitic spray electrodes are able to create a continuous layer on the surface of the polymer with high levels of compliance and homogeneity, leading to performances comparable with traditional powder based electrodes. Finally, the effect of the presence of a rigid substrate on the actuator performances was found to hinder the deformations along the xy-plane of the active polymer, thus limiting the displacement along the z-axis. When stacked configurations are not available, a possible solution to reduce this hindering effect is to create a button-like structure by layering the active polymer on a rubbery material such as a silicone rubber to reduce the superficial friction with the substrate.

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