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Artificial Muscles based on Synthetic Dielectric Elastomers

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***Abstract*—Acrylic copolymers, silicone, and thermoplastic block copolymers have been investigated as artificial muscles. These dielectric elastomers exhibit high actuation strain, pressure, and specific energy density when a high driving voltage is applied across the thin polymer films. I will discuss the chemical and processing aspects that are critical to achieving high actuation performance. One successful example is the highly prestrained acrylic elastomer. We have developed interpenetrating polymer networks (IPN) in which the acrylic network is under high tension balanced by the compression of an additive network were investigated to further enhanced actuation performance. The IPN films at zero or nominal prestrain showed up to 300% actuation strain. The calculated values of maximum actuation energy density and electromechanical coupling factor are 3.5 J/g and 93.7%, respectively. Important actuators enabled by the IPN films and prestrained acrylic films will also be presented.**

I. FUNDAMENTALS OF DIELECTRIC ELASTOMERS

A thin dielectric elastomer film sandwiched between a pair of compliant electrodes is capable of generating large strain and strain rates in response to external electrical stimulation.[1-3] When a high voltage is applied between the electrodes, the electrostatic forces compress the elastomeric film across its thickness direction and expand its area. The actuation pressure is given by

$$p = \varepsilon_r \varepsilon_o E^2 = \varepsilon_r \varepsilon_o (V/z)^2$$

where E is the electric field, ε_r is the dielectric constant, ε_o is the permittivity of free space, V is the voltage, and z is the polymer thickness. Given an elastic modulus Y, the actuation strain, in thickness reduction, can be estimated by

$$s_z = -p/Y = -\varepsilon_r \varepsilon_o (V/z)^2/Y$$

Therefore, the performance of the actuator is determined by the electrical and mechanical properties of the dielectric elastomer. High macroscopic permittivity (dielectric constant), high dielectric breakdown strength, and low modulus are necessary for high actuation stress and strain. High tensile strength would reduce mechanical tearing. For fast actuation speed, low viscoelasticity is essential.

Compliancy of the electrodes is also critically important. Carbon grease and carbon powder are commonly used. Conducting polymers, carbon nanotubes, and even electrolyte solutions have been used to obtain high strain. When an ultrathin layer of carbon nanotubes is used, the electrode can self-clear during a localized dielectric breakdown. This phenomenon has been used to enhance the fault tolerance of the dielectric elastomers.[4]

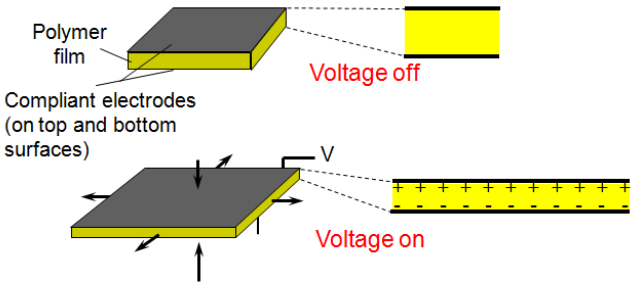

Figure 1. Actuation of a dielectric elastomer film with compliant electrodes. Electrostatic attraction occurs between the electrodes, squeezing the sandwiched polymer. This causes the thickness of the polymer film to be reduced and its area stretched.

II. MECHANICAL PRESTRAIN

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It has been found that prestrain is critically important to achieve high strains and high energy densities in most dielectric elastomers. Figure 2 shows two acrylic films (VHB adhesive tape by 3M) before and after actuation. One film is prestrained biaxially by 300% and exhibits approximately 200% area strain, while the other is uniaxially prestrained by 100%x700% and exhibits a 200% linear strain. The prestrain was found to have little effect on the dielectric constant of the polymers, but it substantially enhances their dielectric breakdown field. As electrically induced strain and stress are both quadratic to the applied electric field, high breakdown strength significantly increases the maximum actuation performance.

Why prestrain increases the polymer's dielectric strength is not yet fully understood. Defects introduced during film production or fatigue can cause dielectric breakdown at electric fields lower than those of the intrinsic material property. Localized pull-in effects, viscoelastic behavior, or high leakage current can also reduce the usable electric field.[5-7] Prestrain should be effective in preventing the pull-in effect as illustrated in Figure 3. For a non-prestrained dielectric elastomer, the characteristic stress-strain chart shows a rapid rise of stress during initial straining, and a plateau, and finally a steep rise until mechanical tearing occurs which involves breaking of covalent bonds. When a constant voltage is applied to actuate the film, the stress and strain will be determined by the quadratic chart. The electric field increases with the inverse of the strain. As such, a sufficiently high constant voltage will continue to drive the film thinner and thinner until the quadratic chart crosses the mechanical stress-strain chart. This induces the pull-in effect and the possible eventual dielectric breakdown. When the same film is highly prestrained, the origin of the charts is moved to O'. The rising Maxwell stress with strain will be less likely to cross the mechanical stress-strain chart. A stable actuation strain is therefore obtained. Prestrain is very effective for the acrylic films and some silinoe elastomers, but is less effective in certain silicone films which may have different stress-strain characteristics than the ones shown in Figure 3.

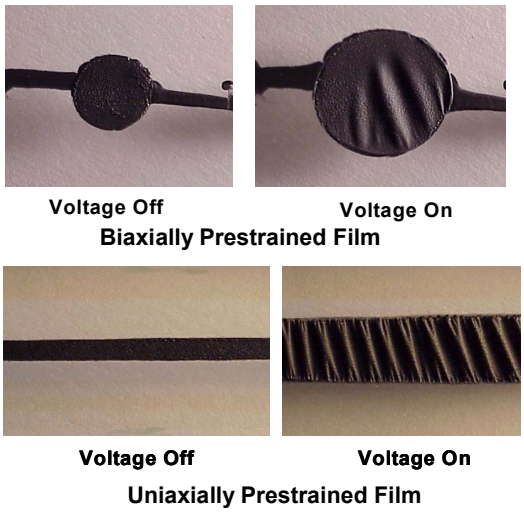

Figure 2. Actuation of acrylic elastomers at 5kV (about 300 V/μm). The films are prestrained on sturdy rigid frames (not shown). The electrodes (the black areas) use smeared carbon grease.

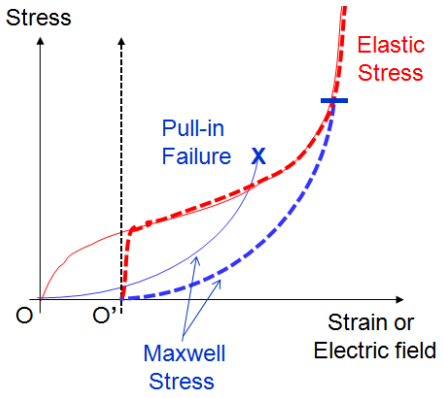

Figure 3. Characteristic stress of a dielectric elastomer film as a function of mechanical strain or electric field (constant voltage condition). The charts with origin at O are for a non-prestrained film and at O' for the prestrained film. The cross (X) indicates dielectric breakdown and the bar (—) indicates stable actuation strain.

III. INTERPENETRATING POLYMER NETWORKS

Prestrain can cause several practical problems including mechanical instability at interfaces between the soft elastomer and the rigid prestrain-supporting structure, as well as stress relaxation and actuator fabrication complexity. There is a rather large performance gap between the intrinsic material capability and the final packaged actuators. It is desirable to reduce or eliminate mechanical prestrain while retaining its performance benefits. We have demonstrated that interpenetrating polymer networks (IPN) as new dielectric elastomers can exhibit high actuation performance without mechanical prestrain.[8] In our approach, the acrylic elastomers were used as the initial elastomeric network to take advantage of the high dielectric breakdown field obtained in highly prestrained acrylic films. Crosslinkable liquid monomers were introduced into highly-prestrained acrylic films and cured to form the second elastomeric network. When the interpenetrating elastomeric network films were allowed to relax to zero external stress, the acrylic network would contract, compressing the additive network. In the resulting free-standing films, the two networks were in balance, one in high tension and the other in high compression. The preserved prestrain of the VHB networks can be varied over a wide range depending on the concentration of functional monomers. Free-standing IPN films were shown to exhibit electrically induced strains up to 300%, comparable to highly prestrained acrylic films (Figure 4).

Dynamic mechanical measurements showed that the IPN films are less viscoelastic than the acrylic films (VHB 4910).[9] From the values of mechanical loss factor ($\tan\delta$), the calculated mechanical efficiency of the materials is higher than that of acrylic films.

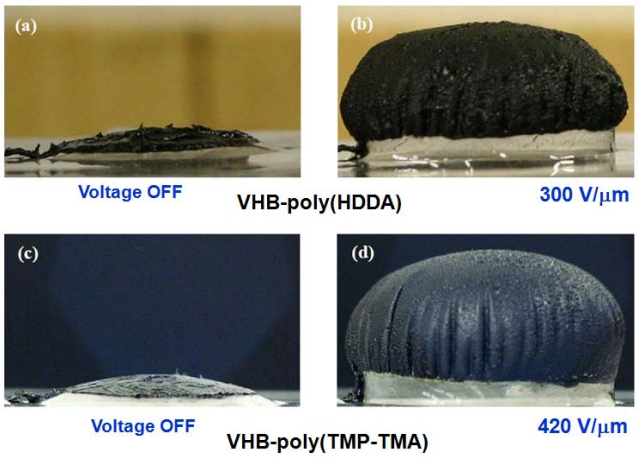

Figure 4. Diaphragm actuators based on IPN films consisting of a VHB network and an additive network of highly crosslinked poly(HDDA) and poly(TMP-TMA). The film is under a constant, small tension maintained by an air pressure bias in the diaphragm chamber.

IV. CONCLUDING REMARKS

Dielectric elastomers represent a radically new category of electrochemically active materials with unprecedented large actuation strain with high stress and specific energy density. Prestrain and IPN of such polymers can significantly alter the actuation property. The peak power density in packaged actuators is on the order of 1 kW/kg. Commercial product development is being pursued, though manufacturing yield and operation stability remain road blocks. These could be overcome with our recently developed self-healing dielectric elastomers.[4] The newer artificial muscles are made fault tolerant through the self-clearability of single walled carbon nanotubes. The actuation lifetime has thus been improved by 2 orders of magnitude.

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