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Artificial muscle: movement and position control

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The movement of an all polymeric triple-layer artificial muscle based on polypyrrole (PPy) that work in aqueous solution was characterised. The magnitude and direction of the experimental current control both rate and direction of the movement. The described angle is a linear function of the consumed charge.

Most of the named polymeric artificial muscles:[1] piezoelectric, electrostrictive, electrostatic, electrophoretic devices, show very fast responses to potential gradients between two metallic electrodes. Nevertheless, in spite of the fact that the frequency of the movement can be controlled, the position of the device relaxes, even under applied potential. Molecular machines such as catenanes and rotaxanes working under electrochemical or chemical control are being developed at the nanometric level.[2]

Here, we show that muscles based on the electro-chemo-mechanical properties of conducting polymers[3,4] move under faradaic control of the electrochemical reactions taking place in the films of a conducting polymer, allowing perfect control of the movement. The oxidation and reduction of conducting polymers are associated with volume changes: an electro-chemo-mechanical property. This property is used to produce micro and macro actuators.[3–6] Volume changes of conducting polymers are induced by the charge-compensating ions flowing into or from the polymer during oxidation or reduction processes. By considering the non-stoichiometric nature of those materials,[5] the concentration of those counterions in the material changes in a continuous and reversible way under electrochemical control. So, those changes of volume in the polymer were transformed to macroscopic, continuous and elegant angular movements by bi-layer[3] and multi-layer actuators.[4]

The synthesis of the polymeric films and the preparation of the triple layer [(PPy(ClO_4))//non-conducting and adhesive doble side tape//PPy(ClO_4)] device have been described previously.[3] Two p-doped polypyrrole films in an intermediate state of oxidation were used to produce the muscle. The dimensions of each polypyrrole film are 2 cm × 1.5 cm × 13 μm thickness and weight 6 mg.

One polypyrrole film was connected to the working electrode of the potentiostat. Both counterelectrode and reference electrode were connected to the second polypyrrole film. In this way, the muscle potential (potential gradient between both PPy films) can be followed during current flow.

The device was immersed in a 1 M $LiClO_4$ aqueous solution. Then it was submitted to different constant currents (ranging from 8 to 35 mA) to describe the same movement of 90°, from the vertical position, every time. Fig. 1 shows the recorded chronopotentiograms: higher currents induce potential rise (as well as Faraday's laws, the system also follows Ohms' law and the film, interfaces and solution resistances originate higher potentials—overpotentials—for rising currents) and faster movements. The angular rate of the movement is a linear function of the experimental current (Fig. 2a). This figure indicates that the experimental current provides perfect control of the angular movement rate. The initial position was recovered by flow of a reverse current every time.

Considering the experimental currents and the times of current flow from Fig. 1, a constant charge was consumed whatever the driving current (Fig. 2b). This is in good agreement with the

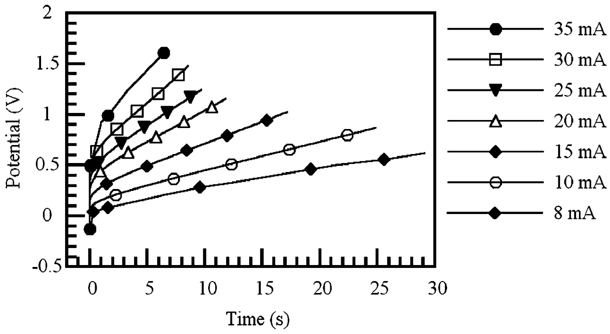

Fig. 1 Chronopotentiograms recorded when a triple layer muscle [2 cm × 1.5 cm × 13 μm], formed by polypyrrole films weighing 6 mg each, was submitted to different currents (8, 10, 15, 20, 25, 30, 35 mA) in a 1 M $LiClO_4$ aqueous solution for the times required to describe an angular movement of 90°.

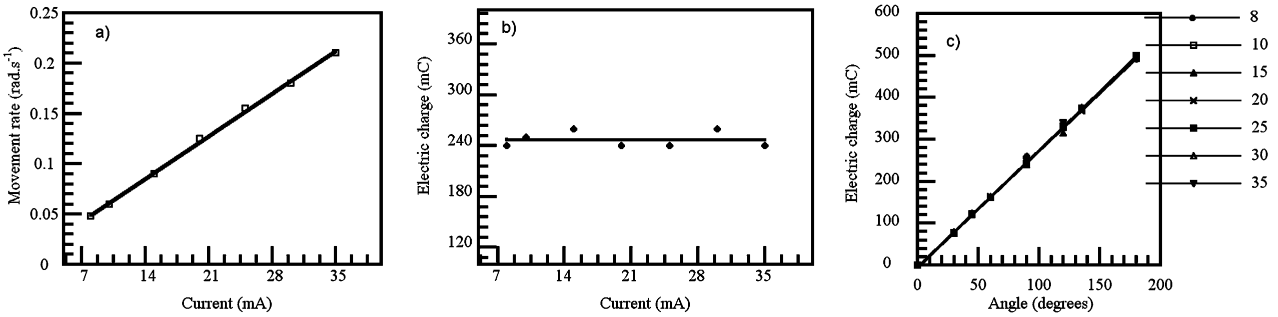

Fig. 2 a) Linear relationship between the applied current and the angular rate determined from the times required to describe an angular movement of 90° under the experimental conditions from Fig. 1. b) Electric charge consumed by the triple layer muscle from Fig. 1 to move through 90°. c) Electric charge consumed by the triple layer muscle under the experimental conditions defined in Fig. 1 to describe different angles (30, 45, 60, 90, 120, 135, and 180°) under the different currents studied. Experiments in 1 M $LiClO_4$ aqueous solution.

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hypothesis that the electrochemical reaction (the consumed charge) controls throughout the composition the volume change of the polypyrrole films. Thus, the same charge is consumed, producing the same variations of volume and describing the same angle under different current flow. The conclusion is perfect control of the device position (angle) by the charge consumed. Fig. 2c shows the experimental results of this relationship whatever the experimental current to move across different angles: the slope is 2.7 mC deg^{-1} which is the charge required to move the free end of our muscle by 1°. Now we can attain any angle by establishing the initial position and angle. The charge required to attain the new position will be given by eqn. (1). The direction of the current will be established to describe positive or negative angles. Any attained angular position is stable when the current is switched off and only can be modified by redox processes (chemical or electrochemical) acting on the polypyrrole composition. Even muscles trailing steel pieces adhered to their bottom remain contracted for hours without any relaxation. This is one of the main differences between polymeric actuators based on conducting polymers and those mentioned in the first paragraph of this paper.

$$Q = \text{angle (degree)} \times \text{slope (mC deg}^{-1}) \qquad (1)$$

So, the driving signal includes control of both position and movement rate of polypyrrole muscles. Both linear relationships, charge *vs.* angle (Fig. 2c) and current *vs.* angular rate (Fig. 2a), support the faradaic origin of the movement. In both cases the charge is consumed to oxidize and reduce, respectively, each of the muscle polypyrrole films. The involved charge in these electrochemical reactions defines the symmetrical variation of the oxidation depth in both PPy films, which establishes the angular movement. The oxidation depth controls the stress gradient along the muscle: from the expansion on the PPy acting as anode to the contraction on the PPy acting as cathode. Under those conditions, if we are able to reproduce the same material to manufacture different devices, regardless of the dimensions (length, width or thickness of the muscle) any physical characteristic of the movement should be under control of the oxidation depth. Hence 13 different muscles having different dimensions were constructed and checked, each under five current densities. The experimental results showing the angular rates measured from repeated angular movements of 90°, as a function of the change of the oxidation depth (mA mg^{-1}, equivalent to mC s^{-1} mg^{-1}), are depicted in Fig. 3. A good linear relationship was obtained proving both the good reproducibility of the experimental procedure to produce devices whose actuation is not dependent on the dimensions and, once again, the electrochemical origin of the movement.

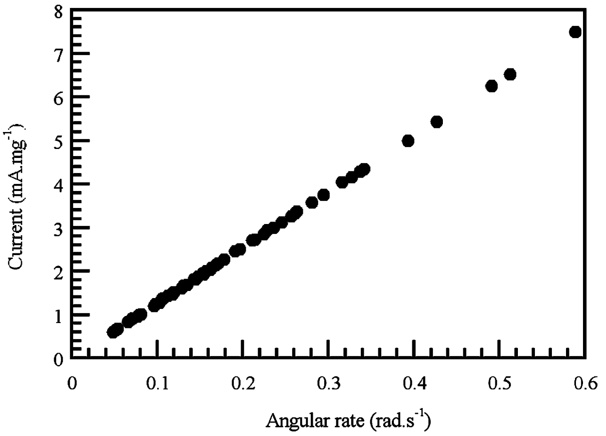

Fig. 3 Angular rate measured for a movement of 90° using triple-layer muscles of different dimensions (including different weights of polypyrrole films: 8.3, 7.8, 7.4, 6, 5.5, 5.1, 5, 4, 3.7, 3.5, 3, 2.3 and 2 mg) in 1 M $LiClO_4$ aqueous solution under different currents (10, 15, 20, 25 and 30 mA).

Fig. 4 Transversal fissure attained by material fatigue after more than 300 cycles of angular movement, 90° each, obtained by a flow of ±15 mA.

The life time of the muscles describing angles lower than 90° is greater than 300 cycles under a constant reverse current of 15 mA. After this time a fissure is produced by mechanical stress at the solution/air interface (Fig. 4). If the electrical connections are carried out under this fissure a new life time of around 300 cycles is obtained. No significant de-lamination is observed.

In conclusion we have produced macroscopic electro-chemo-mechanical devices, or artificial muscles, having perfect control of their movements. The magnitude and direction of the experimental current controls both the rate and direction of the movement: the movement can be accelerated, reversed or stopped at any time under perfect electrochemical control. The described angle is a function of the consumed charge producing a positioning device. These actuators produce smooth, uniform and elegant movements mimicking those from animals or human beings, suggesting the possibility of more human like robots. Using a large number of samples with different dimensions it was proved that the linear law relating the bending angle to the consumed charge is a general property for this kind of sample. Under these conditions the way is open for “mass” production of actual devices.

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