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Reliability tests of ionic polymer metallic composites in dry air for actuator applications

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ABSTRACT

Electroactive polymers (EAPs) are capable of exhibiting large shape changes in response to electrical stimulation. EAPs can produce a large deformation with a low applied voltage for actuation applications. The IPMC (Ionic Polymer Metal Composite) is a well-known type of ionic EAP. It has numerous attractive advantages, such as low electrical energy consumption and being lightweight. The underlying mechanism of an IPMC actuator is the ionic diffusion when a voltage gradient is applied. As such, the characteristics of the ionic solution have a large impact on the physical properties of the IPMC. In this paper, reliability tests of IPMCs with a non-aqueous ionic solution are demonstrated. The Pt-IPMC with LiOH aqueous solution exhibits the best maximum displacement, but the water in the LiOH solution is electrolyzed easily because of the low electrolysis voltage (1.23 V) of water. To ameliorate the electrolysis problems and improve the operation time, more appropriate solvents with a high electrolysis voltage and low vapor pressure should be chosen. Parylene-coating can also protect the IPMC from solvent loss. The reliability tests focus on the durability of IPMCs in dry air. Improvements in IPMC fabrication, such as Ag-IPMC, are discussed in this paper. Through the use of parylene protection and an ionic solution with a high electrolysis voltage, the lifetime of the Ag-IPMC in dry air is up to 15 times greater than that of the uncoated Ag-IPMC with aqueous solution. We have addressed potential issues regarding the dry air actuation of IPMCs, and found that the cracking of electrodes has a major impact on the reliability of the IPMCs in this study.

1. Introduction

Electroactive polymers (EAPs) are a promising technology for micro actuators. Compared to inorganic materials, these versatile polymers have several attractive properties, such as being lightweight, inexpensive, and easy to manufacture. Electroactive polymers have been widely discussed in the field [1–2]. Previous studies have suggested that under the right external electrical activation mechanism, electroactive polymers can change their sizes and shapes, signifying that they can convert electrical energy into mechanical energy. Moreover, EAPs can produce a large deformation with a low applied voltage, and can thus be used as actuators [3].

EAPs are classified depending on the mechanism responsible for actuation, and fall under either electronic EAPs or ionic EAPs. The most typical ionic EAP is the ionic polymer metallic composite (IPMC), which basically consists of an ion exchange polymer membrane, two coated electrodes, and mobile cations. An IPMC can display muscle-like behavior when a voltage gradient is applied, and this behavior has contributed to its popularity. The behavior is mainly due to the diffusion of free ions, which makes possible the deformation mechanism of IPMCs [4,5].

Nemat–Nasser and Zamani have reported on the mechanism underlying the failure of IPMC operation in open air [6]. They pointed out the limitations of using water as a solvent (e.g. electrolysis starts at 1.23 V; evaporation occurs at room temperature). They also discovered that IPMCs with an ionic solution have a greater solvent uptake, and can be subjected to a higher voltage without electrolysis. Compared to water, IPMCs with an ionic solution can be actuated in open air for long time periods. Ionic liquids used as liquid electrolytes have been studied previously [7]. Electrolytes are ubiquitous and indispensable in all electrochemical devices. The electrolytes serve as a conducting medium, in the form of ions for the transfer of charges between a pair of electrodes. The vast majority of electrolytes are electrolytic solution-types that consist of salts (also called “electrolyte solutes”) dissolved in solvents. The salts of ionic liquids are added to water or non-aqueous solvents that remain in the liquid state over the service-temperature range; based on this, we can try to add lithium salts to non-aqueous solvents to produce non-aqueous liquid elec-

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trolytes, thereby improving the performance of IPMCs by using high electrolysis voltage ionic solution to alleviate the electrolysis problem.

For IPMCs fabricated with platinum electrodes, the voltage used to drive the IPMC is much higher than the electrolysis voltage of the actual ionic solution, where electrolysis can occur. To solve this problem, the soft metal silver, instead of platinum, can be applied to make IPMCs more flexible [8]. Moreover, expect to reduce the driving voltage by using silver which has the advantage of a low resistance and large ductility, thereby alleviating the electrolysis problem.

IPMCs require some level of hydration as their actuation mechanisms depend on the internal movements of ions. Although the organic solvent, propylene carbonate, has a lower vapor pressure compared to water, solvent loss still occurs during operation. We thus assumed that, an encapsulated IPMC will be protected from drying out when operated in air for long periods. Parylene coating technology is discussed in this work. Parylene is the trade name for a variety of chemical vapor deposited poly(*p*-xylylene) polymers used as moisture and dielectric barriers. Parylene is a conformal protective polymer coating material utilized to uniformly protect any component configuration on such diverse substrates as metal, glass, paper, resin, plastic, ceramic, ferrite and silicon. Because of its unique properties, Parylene conforms to virtually any shape, including sharp edges, crevices, points; or flat and exposed internal surfaces. We try to improve the reliability of IPMCs by formed the waterproof interface which is Parylene C on the IPMC surface to prevent the solution loss.

In the following sections, we discuss how to choose an appropriate ionic solution, electrolyte, waterproof coating, and lower voltage driven electrode. Various samples were prepared and tested in dry air. Conclusions are given at the end of this paper.

2. Material selection and optimization

2.1. Ionic solution and metal salts

To ameliorate electrolysis problems and improve the operation time in air, more appropriate solvents should be chosen instead of water. The electrolyte solvents should possess the following properties at a minimum: Firstly, the solvents should be able to dissolve lithium salts to a sufficient concentration. Secondly, the viscosity of the solvents should be low, so that fast ion transport can occur within the electrolyte. Thirdly, the solvents should remain liquid over a wide temperature range, which is beneficial for operation and storage. In other words, a low melting and a high boiling temperature are desirable. Lastly, Lopes and Costa Branco have mentioned that the higher the dielectric permittivity is, the higher the electrolysis voltage is [9]. Thus, solvents with a high dielectric permittivity are suitable for IPMCs. In addition, the evaporation rate is related to vapor pressure. A low vapor pressure results in a low evaporation rate. Water is easy to evaporate because of its high vapor pressure. In summary, the aforementioned study explored the major advantages of propylene carbonate (PC), which is usually used as an organic polar solvent. PC is a carbonate ester derived from propylene glycol. Compared to water, propylene carbonate has a much lower vapor pressure. It also has a high dielectric permittivity ($\epsilon = 69$) and a wide liquid range (−49–242 °C). After adding electrolyte salts in both water and PC, the dielectric permittivity of lithium ions in propylene carbonate was almost two times higher than that of lithium ions in water.

As reported in a previous study on IPMCs, a LiOH aqueous solution is the best electrolyte to achieve maximum displacement. The lithium ion was chosen as the exchange ion in this study by Shahinpoor et al. [10]. However, LiOH is almost insoluble in propylene carbonate. Kang Xu reported on the ionic conductivity of different lithium salts in PC, and the results are presented in Table 1 [11]. Ionic conductivity is the movement of an ion from one site to another through defects in the crystal lattice of a solid or in an aqueous solution. The higher the ionic conductivity is, the faster the movement of ions in IPMCs can be. While LiAsF6 shows the highest ionic conductivity, it is toxic and not safe for general usage. We thus chose $LiClO_4$ instead, due to its non-toxicity, high ionic conductivity, and high solubility. $LiClO_4$ is usually used as an electrolyte salt in non-aqueous electrolyte solutions in lithium batteries. Due to the large size of the ClO_4^- anion, the solubility of $LiClO_4$ in some organic solvents is much larger than that of NaCl, Li_2SO_4, LiCl, and Na_2SO_4 [12]. As a general rule, lithium salts with large anions are suitable as electrolyte salts for use in aprotic organic solvents.

Table 1
Ionic conductivity of different lithium salts in PC.

Lithium salt	$LiBF_4$	$LiClO_4$	$LiAsF_6$	$LiCF_3SO_3$	$LiN(CF_3SO_2)_2$
Ionic conductivity(10^{-3} S/cm)	3.4	5.6	5.7	1.7	5.1

The actuation mechanism of non-aqueous IPMCs is illustrated in Fig. 1. The flexible polymer membrane covered by a metallic electrode can absorb the non-aqueous solution. When the driving voltage is applied, the polar solvent molecules associated with the lithium ions move toward the anode. However, the anions are in a fixed position because of the structure of the membrane. The IPMC therefore changes its shape due to the ion movement.

The cathodic limiting reaction of propylene carbonate containing $LiClO_4$ has been shown to be a reduction to propene and carbonate. The anodic reaction is an oxidation to CO_2 [13]. $LiClO_4$ with PC was used in this experiment. From the I–V curve presented in Fig. 2, it is clear that due to the dissociation of the ions, electrolysis is observed at a voltage of approximately 2.3 V, resulting in a loss of solvent connection and hence a loss of the actuation capabilities of the IPMC. Fig. 3 shows an approximate over-potential of 0.2 V due to the resistance of the electrodes. [14] Comparing the IPMC in a non-aqueous solution to a hydrated IPMC, a much higher driving voltage can be used to control the non-aqueous electrolyte IPMC with minimal electrolysis. This result also proves that a higher dielectric permittivity generates a higher electrolysis voltage [15].

2.2. Lower resistance through the use of silver metal

The typical Pt-IPMC (IPMC sandwiched by platinum electrodes) still has many areas ripe for improvement. Considering the energy loss and the intended application in opto-electro–mechanical systems, we aim to decrease the voltage to as low a level as possible, even though the electric potential gradient for driving the IPMC will

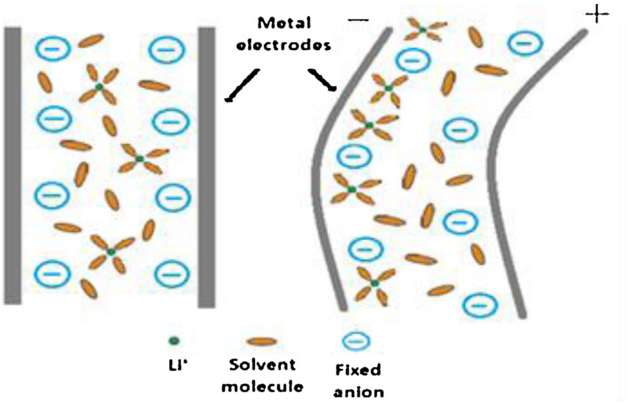

Fig. 1. The actuation mechanism of non-aqueous IPMCs.