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Improving the performance of IPMCs with a gradient in thickness

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Abstract

An ionic polymer metal composite (IPMC) is a kind of electro-active polymer. Due to the properties of low driving voltage, large deformation, flexibility and lightness, it is becoming one of the more popular from a diversity of smart materials. In this study, a novel structure of Nafion® film is proposed to improve the performance of an IPMC. IPMC samples with a gradient structure in thickness are fabricated and their performance is investigated to confirm the validity of the gradient structure. The deformation displacement and the blocking force are compared under AC and DC voltage by experiments. The results indicate that the structure of gradient in thickness would improve the performance both in deformation displacement and blocking force.

(Some figures may appear in colour only in the online journal)

1. Introduction

An IPMC is a new kind of electro-active polymer which has a 'sandwich' structure. It comprises three layers: one ion exchange film between two thin metal electrode layers. The inherent property of an IPMC has many advantages, such as flexibility, lightness, chemical stability and fast response, etc. The most attractive property is the large bending deformation under low driving voltage [1–3]. The bending deformation of an IPMC is generated by redistribution under electrical stimulation of its internal water molecules. When the electric field is applied across the thickness of an IPMC, the hydrated cations with water molecules move together towards the cathode which results in swelling near the cathode side and contraction near the anode side of the IPMC. The internal extensional stress of the polymer causes the IPMC to bend towards the anode direction [4, 5]. An IPMC can also output an electrical signal under the deformation of an external force, so it could be used as both actuator and sensor; this has significant potential in a wide range of applications, including the field of biomimetics, robotics, medical devices and aerospace. The major drawback which greatly limits the application of IPMCs is the low blocking force and response frequency. The challenge of IPMCs is mainly about accurately controlling the interaction of mechanical, electrical and chemical properties in the ionic polymer [6–9].

A great deal of research has been carried out into improving the performance, environment adaptability and applicability of IPMCs. Several new fabrication methods have been developed, such as physical metal loading, hot-pressing, using new materials as electrodes, etc. Kim *et al* studied the performance of IPMCs with various thicknesses for extensive application [10]. Bennett *et al* used an ionic liquid to replace water as the solvent to improve the stability of the IPMC's performance in air [11]. Lee *et al* proposed hot-pressing to fabricate thick IPMCs and performed several cycles of Pt electroless plating to improve the actuating performance [12]. Fukushima *et al* developed a dry actuator that was fabricated by layer-by-layer casting of bucky gel. The advantage of the actuator is durability in air [13, 14]. Akle *et al* proposed a new manufacturing technique of direct assembly process to fabricate large strain ionic polymer transducers, in which the electrode material was sprayed onto ionic-liquid Nafion® and hot-pressed [15–17]. Nguyen *et al* used Nafion® layered silicate and Nafion® silica nanocomposites to fabricate IPMCs; the blocking force is greatly improved with limited relaxation [18]. Plasma treatment was introduced to roughen the Nafion® surface in

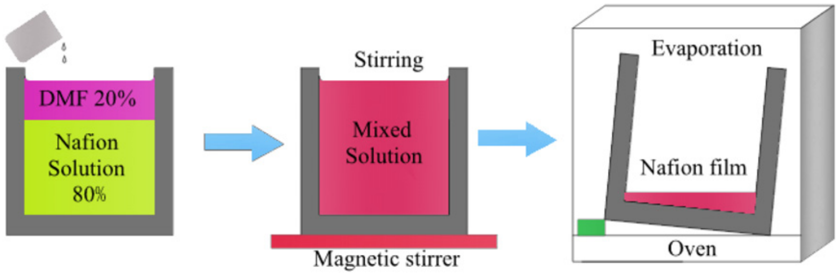

Figure 1. The casting procedure of gradient Nafion® film.

order to improve the actuation performance of IPMCs [19]. Chung *et al* proposed micro-fabrication technologies by applying silver nano-powders for the fabrication of IPMCs to improve the adhesion between electrodes and polymer without surface roughening pretreatment [20]. Mukai *et al* used millimetre long single walled carbon nanotubes to obtain a quick response and large bending actuator [21]. Palmre *et al* introduced carbon aerogel as a new material for the fabrication of nanoporous electrodes for EAP actuators using the direct assembly process [22]. Yip *et al* developed CNT ionic polymer actuators and the performance can be tuned by the addition of different CNT concentrations [23]. All these studies are aimed at improving the performance by using new materials in the polymer, increasing the thickness of the Nafion® film, changing the electrode materials or solvent, etc. On the other hand, the performance of an IPMC can vary with its thickness, the bending stiffness and electric field of the Nafion® film can be affected by the thickness of the IPMC.

In this study, the IPMC is fabricated with a Nafion® film with a novel structure of gradient in thickness. The films with a uniform structure and different gradient structures are cast by the same volume of Nafion® dispersion. The gradient IPMC which was fabricated by electroless plating is used to determine how the performance changes. The deformation displacement test and blocking force measurement under AC and DC voltage are compared between uniform and gradient structure in this paper.

2. Experiment

2.1. Casting gradient films

Typically, the commercialized ion exchange polymer Nafion® film from DuPont™ is used to fabricate the IPMC. The performance of the IPMC varies with its thickness, such as deformation, blocking force etc. The commercially available Nafion® film is uniform with thickness varying from 20 to 183 μm [24]. To achieve the desired gradient Nafion® film, the casting method with Nafion® dispersion from DuPont™ is used in this work. The casting procedure of gradient Nafion® film is illustrated in figure 1.

Nafion® dispersion and dimethylformamide (DMF) are poured into the casting mould with dimensions of 50 mm × 15 mm × 40 mm (length × width × height). The volume of the Nafion® dispersion (D520, polymer content 5 wt%) is 15 ml and the volume of DMF is 1/4 of that of the Nafion® dispersion. The use of DMF is to prevent surface cracks in solidified Nafion® during solvent evaporation. Tetraethylorthosilicate (TEOS) is another additive to improve the intensity and keep the internal water molecules of the IPMC. The amount of TEOS is 5% of whole solution by weight.

Next, the mixed solution is stirred with a magnetic stirrer to make the solution homogeneous (sometimes ultrasonic cleaner is used to eliminate bubbles in this step). The solution is then placed in a constant-temperature drying oven. In order to cast the gradient film, the casting mould is placed at a tilt. The mould must be keep level to get the uniform film. The solvent is fully evaporated at 70 °C in the oven. It takes almost 20 h to form the film; the temperature is then raised to 100 °C for 3 h to improve the mechanical stiffness of the film and anneal at 140 °C for 15 min to relieve the stress in the film. Finally, the gradient Nafion® films are cast and conserved in de-ionized water.

2.2. Fabrication of the IPMC

The electrodes of Pt attached to both sides of the cast Nafion® film are fabricated by electroless plating. The electroless plating method is as follows: First, 1500# sandpaper is used to roughen the surface of the film along one direction to increase the interfacial area so that it would help the electrodes material deposits. Then the film is rinsed chemically with H_2SO_4 (0.5%) and H_2O_2 (15%) solution; afterwards, the film is rinsed with boiled de-ionized water and dipped into H_2SO_4 (0.5%). Second, the film is dipped into the solution of $[Pt(NH_3)_4]Cl_2$ (3 mg mm^{-2}) for about 14 h to accomplish ion exchange. Third, the platinum complex cations are reduced to the metallic state by using the reducing agents $NaBH_4$ (5%); the reaction temperature is from 40 to 60 °C. Then the Pt is deposited on the surface of the film. Fourth, the film is prepared for the second reduction reaction by rinsing in ultrasonic cleaners after the first reduction reaction. Fifth, the solution of hydrazine hydrate (20%) and the solution of hydroxylammonium chloride (5%) are used to perform the second reduction as the reducing agents. After this reduction, the IPMC sample is fabricated. Then the IPMC sample is rinsed with de-ionized water and stored in a solution of LiCl for experiment.

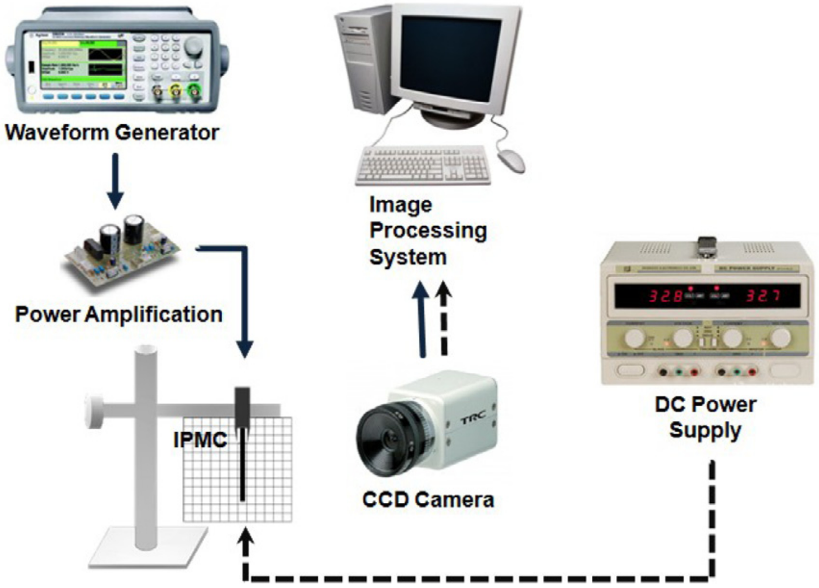

Figure 2. Deformation displacement test system.

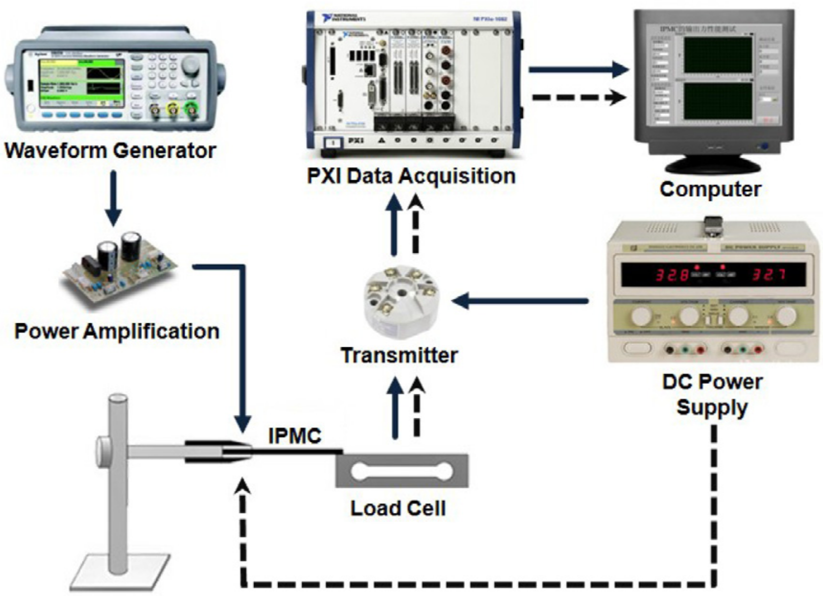

Figure 3. Blocking force measurement system.

2.3. Experimental setup

The main performance characteristics of IPMC are deformation displacement and blocking force. Therefore, the deformation displacement test system and the blocking force measurement system is established, respectively. The experimental setup of the deformation displacement test system is shown in figure 2. The IPMC is gripped in front of the coordinate paper (1 mm × 1 mm per grid), the actuated deformation process is captured by digital camera, and then the displacement data is acquired by an image processing system in a PC. The experimental setup of the blocking force measurement system is shown in figure 3. The blocking force is measured by a load cell (XH10-5g) and data acquisition is by National Instruments™ PXI system with PXIe-6361(DAQ). The solid arrow line stands for ‘actuated by AC voltage’ of the waveform generator (Agilent 33522A). The dotted arrow line stands for ‘actuated by DC voltage’ of the DC power supply.

3. Results and discussion

One uniform Nafion® film and two different gradient films were cast to fabricate the IPMC. The thickness was 0.42 mm uniform, 0.37–0.47 mm and 0.22–0.54 mm, respectively. The average thickness of the films was nearly 0.42 mm. The schematic of IPMCs cast with different gradient in thickness is illustrated in figure 4. 1#, 2#, 3# stand for the

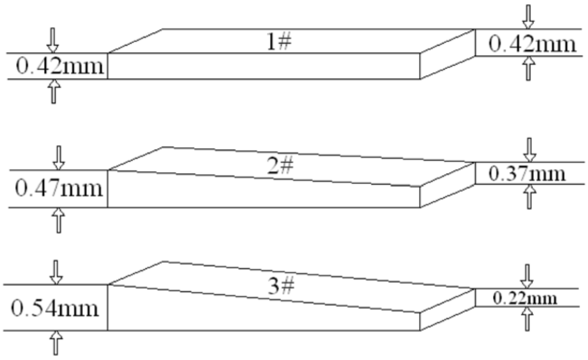

Figure 4. Schematic of the cast Nafion® film with different gradient.

IPMC with thickness of 0.42 mm uniform, 0.37–0.47 mm, 0.22–0.54 mm, respectively. After electroless plating platinum as the electrodes of the IPMC, the edges of the the IPMC need to be cut away otherwise it would cause a short circuit. The IPMC was cut away around the edge by a pair of scissors. The dimension of each IPMC is 35 mm × 7 mm for testing.

In the displacement test, the IPMC was clamped by the thick end. The length of the IPMC is 30 mm outside of the clamp. The IPMC was actuated under 0–3.5 V DC. Deformation images of the IPMC with different gradients were recorded in figure 5. Obviously, the deformation of 2# IPMC almost reaches 90° under 3.5 V DC.

Figure 6 shows the deformation displacement of each IPMC under 0–3.5 V DC. The result in figure 6 shows that the deformation displacement of gradient IPMC is almost similar to the uniform IPMC below 3 V. When the driven voltage was 3.5 V DC, the displacement of 2#IPMC was almost 40 mm which is better than that of the uniform IPMC. 2#IPMC exhibits the best deformation performance driven by DC voltage.

A 0.1 Hz and a 0.5 Hz sinusoidal input voltage with an amplitude that varied from 0 to 3.5 V at 0.5 V intervals was applied to the IPMC. The displacement of the IPMC is measured between the upper and lower positions. The result of displacement of the IPMC driven by AC voltage is shown in figures 7 and 8, respectively. Remarkably, the deformation displacements of gradient IPMCs are better than that of the uniform IPMC. Furthermore, the deformation displacement driven by low frequency is better than high frequency of the sinusoidal wave and the displacement decreases as the frequency increases. The maximum displacement of gradient IPMCs driven by an AC voltage was almost 17 mm at 0.1 Hz with the amplitude 3.5 V which is two times larger

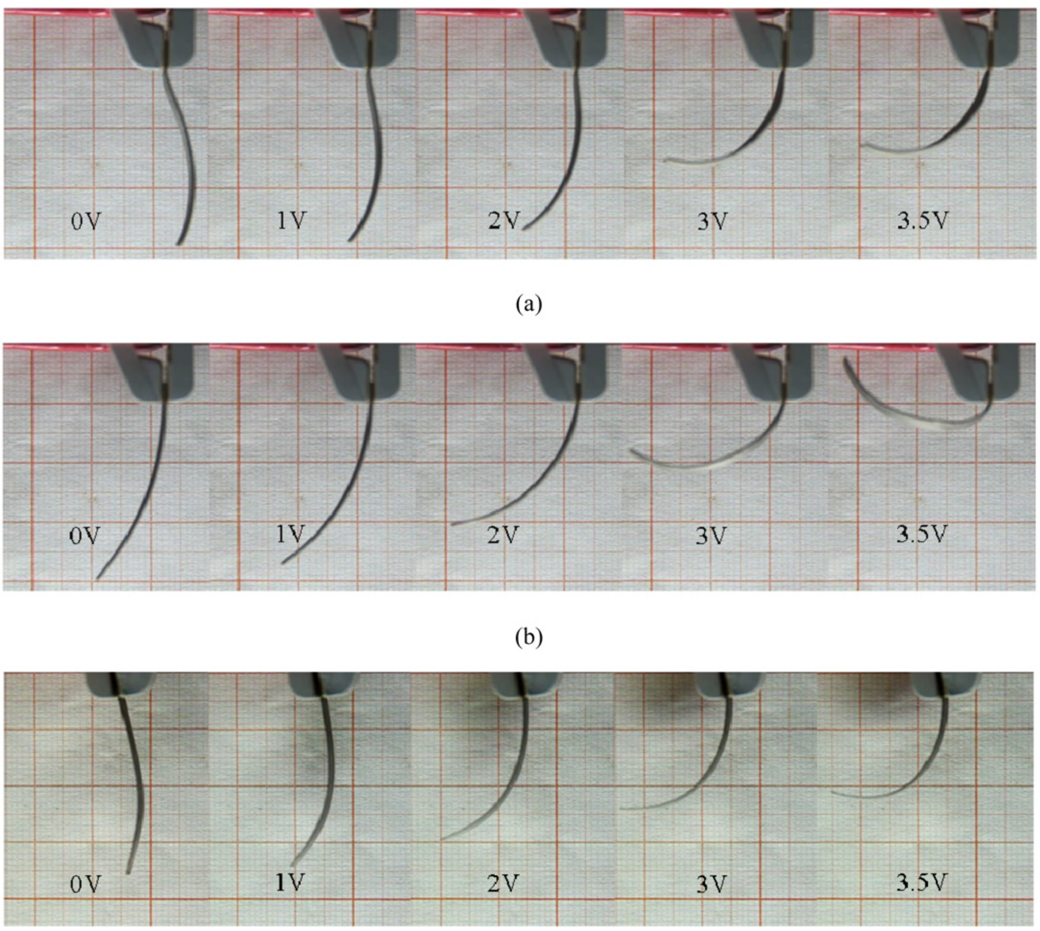

Figure 5. The deformation of the IPMC under 0–3.5 V DC: (a) 1# IPMC; (b) 2# IPMC; (c) 3# IPMC.

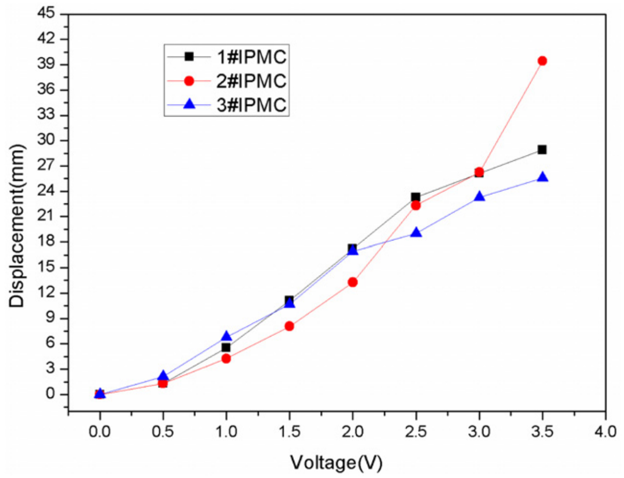

Figure 6. The deformation displacement of IPMC under 0–3.5 V DC.

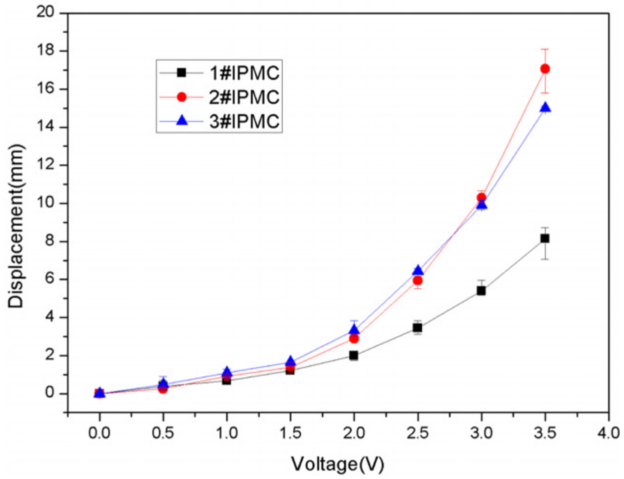

Figure 7. The deformation displacement of the IPMC under 0.1 Hz 3.5 V.

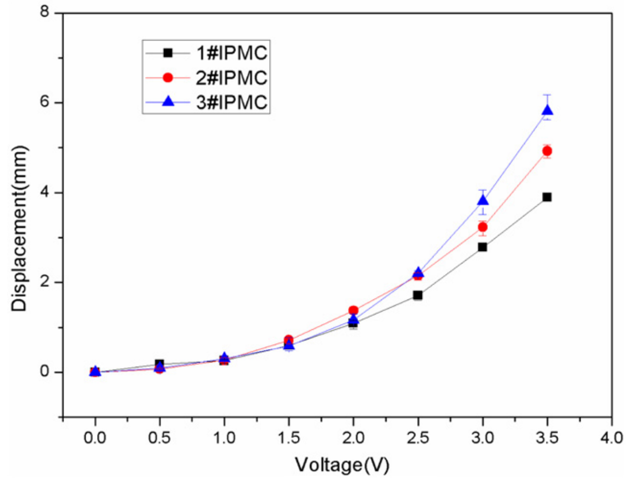

Figure 8. The deformation displacement of the IPMC under 0.5 Hz 3.5 V.

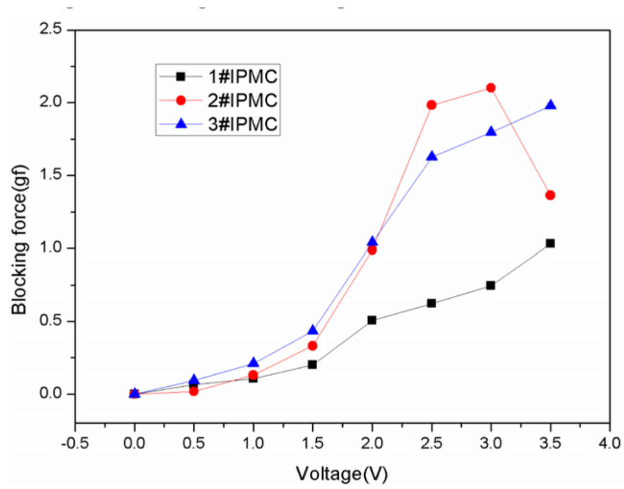

Figure 9. The blocking force of the IPMC under 0–3.5 V DC.

than the displacement generated by the uniform IPMC. From these results of the displacement test, although the average thickness of the gradient and uniform IPMC are the same, the bending stiffness of the forepart of the gradient IPMC is lower than that of a uniform IPMC. Therefore, the forepart of the gradient IPMC is easy to deform and exhibits better performance of deformation than that of the uniform IPMC.

Figure 9 shows the result of blocking force measurement under 0–3.5 V DC. The blocking force of the IPMC under a 0.1 Hz and 0.5 Hz sinusoidal input voltage with amplitude varying from 0 to 3.5 V at 0.5 V intervals is shown in figures 10 and 11, respectively. The blocking force of the IPMC keeps increasing with increase in the DC voltage. The blocking force of gradient IPMCs is much better than that of the uniform IPMC. The maximum of gradient IPMCs is almost two times larger than that of the uniform IPMC. In figure 9, the blocking force of 2# IPMC began to decrease at 3.5 V, which is caused by the relaxation back phenomenon (perhaps caused by the effects of the fabrication process). When the AC voltage is applied to the IPMC, the gradient IPMCs also show better performance of the blocking force than the uniform IPMC. Meanwhile, low frequency voltage results in a larger blocking force than high frequency voltage because the IPMC has more time to reach the maximum of the blocking force. The gradient structure makes the bending stiffness different along the gradient direction. The clamping end of the gradient IPMC is thicker than that of the uniform IPMC, and it provides higher bending stiffness and elastic pressure; as a result it generates a higher blocking force.

4. Conclusions

In this study, a novel structure of cast Nafion® film is proposed to fabricate an IPMC with a gradient in thickness by using electroless plating. Three Nafion® films were cast with thickness 0.42 mm uniform, 0.37–0.47 mm and 0.22–0.54 mm, respectively. By using these Nafion® films, the IPMCs were fabricated with the dimension of 35 mm × 7 mm. The experiments of displacement test and blocking force measurement were carried out to verify

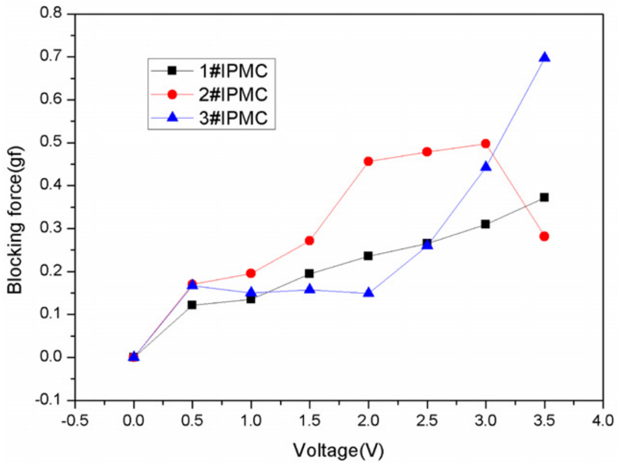

Figure 10. The blocking force of the IPMC under 0.1 Hz 3.5 V.

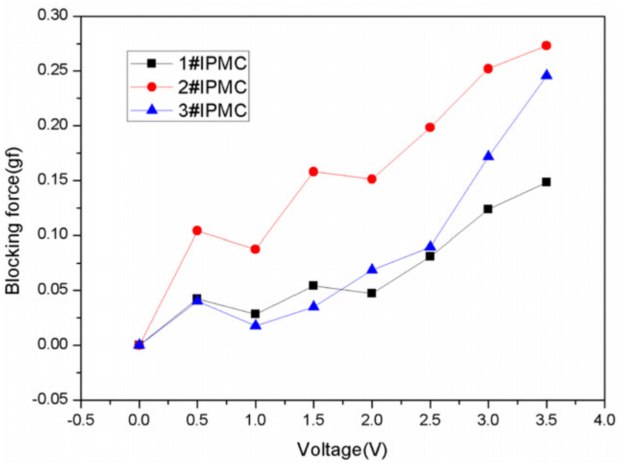

Figure 11. The blocking force of the IPMC under 0.5 Hz 3.5 V.

how the performance changes for practical use. The results show that the performance of the IPMC is improved both in deformation displacement and blocking force with a gradient structure in thickness. The low bending stiffness in the forepart of the gradient IPMC makes it easy to deform and generates a larger displacement than the traditional uniform IPMC, while the bending stiffness is high near the clamping part and that is good for higher blocking force output. Therefore, gradient IPMCs would be further studied and widely used as actuators or sensors in smart materials and applications. Additionally, it is essential to investigate the influence of gradient changes on properties of IPMCs in future studies.

Acknowledgments

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