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Anisotropic surface roughness enhances bending response of ionic polymer-metal composite (IPMC) artificial muscles

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ABSTRACT

Demands from the fields of bio-medical engineering and biologically-inspired robotics motivate a growing interest in actuators with properties similar to biological muscle, including ionic polymer-metal composites (IPMC) – the focus of this study. IPMC actuators consist of an ion-conductive polymer membrane, coated with thin metal electrodes on both sides and bend when voltage is applied. Some of the advantages of IPMC actuators are their softness, lack of moving parts, easy miniaturization, light weight and low actuation voltage. When used in bio-mimetic robotic applications, such as a snake-like swimming robot, locomotion speed can be improved by increasing the bending amplitude. However, it cannot be improved much by increasing the driving voltage, because of water electrolysis. To enhance the bending response of IPMCs we created a "preferred" bending direction by anisotropic surface modification. Introduction of anisotropic roughness with grooves across the length of the actuator improved the bending response by a factor of 2.1. Artificially introduced cracks on the electrodes in direction, in which natural cracks form by bending, improved bending response by a factor of 1.6. Anisotropic surface modification is an effective method to enhance the bending response of IPMC actuators and does not compromise their rigidity under loads perpendicular to the bending plane.

Keywords: IPMC actuator, artificial muscle, bending response, surface roughness, anisotropic, surface modification, cracks, buckling, rigidity.

1. INTRODUCTION

In the fields of biologically-inspired robotics and bio-medical engineering there is a growing interest in new type of actuators, which have properties similar to biological muscle [1]. Various types of materials have been considered for this task. Along with ionic polymer metal composites (IPMC), these include piezo-electric and ferroelectric materials [2, 3], conductive polymers [4] and recently carbon nanotubes [5]. Another class are the soft dielectric materials with electrodes on each side, which can stretch more than 100% by electrostatic forces when strong electric fields with ~100V/μm are applied [6]. IPMC actuators, which are the focus of this study, consist of an ion-conductive polymer membrane, coated with thin metal electrodes on both sides. Compared with other types of materials considered for artificial muscle applications, the IPMCs have the advantages of being lightweight and powered by low voltage. IPMCs can be manufactured from bio-compatible materials such as Nafion® polymer membranes [7] and platinum or gold. IPMCs can be easily cut into very small sizes and various shapes and this makes them very suitable for MEMS actuators.

One of the most attractive characteristics of artificial muscles is their flexibility, which makes them suitable to mimic the soft natural motion of living organisms. Our group has realized a snake-like (or eel-like) swimming robot in which locomotion is achieved by sending a traveling wave along the sectioned IPMC [8-10].

The maximum speed achieved during the experiments was 0.8 mm/s at frequency of the sine wave 8 Hz and input voltage amplitude 2 V [8]. Fish increase their swimming speed by either increase of the frequency of the tail beat, or

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increasing its amplitude. Our past experimental data have shown that the increase of the frequency above 8 Hz results in slower speed of swimming [8], probably, due to the dynamic characteristics of the IPMC. This leaves the increase of the amplitude as the only viable alternative. Due to the use of gold electrodes and alternating current, the driving voltage of 2 V is already much higher than the 1.23 V needed to break the water molecule to hydrogen and oxygen by direct current and platinum electrodes. Because of this, the bending amplitude increase cannot be achieved by further increase of driving voltage amplitude. In this paper we investigate the possibility of increasing the bending amplitude of IPMC, when it is operated at voltage below the water electrolysis voltage.

One approach to achieve higher bending amplitude is to use very thin IPMC films, as past research have shown [11] that deflection is inversely proportional the third power of thickness. Too thin IPMC films, however, do not have the necessary rigidity, when loaded in the plane perpendicular to the plane of bending. Fig. 1 shows the buckling and twisting of a thin IPMC film (60 μm) under its own weight, when held horizontally. The ability of the film to carry loads in this direction is of critical importance for the payload capacity of the snake-like swimming robot. Clearly, compromising actuator's rigidity in the loading plane which is perpendicular to the bending plane (Fig. 2) is undesirable.

The purpose of the present study is to increase the bending response of IPMC actuators, under the following limitations: 1) driving voltage below the onset of electrolysis at about 1.2 V, and 2) maintain rigidity in the loading plane, which is perpendicular to the bending plane. We intend to achieve this by anisotropic surface modification of the IPMC actuator.

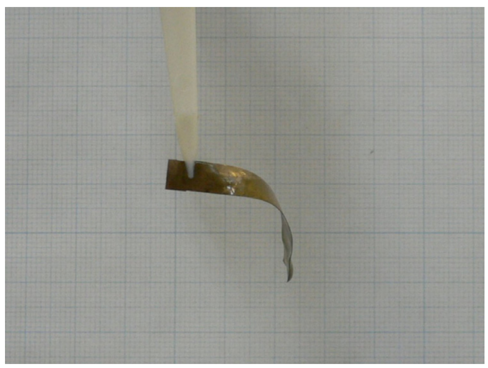


Fig. 1. Thin (60 μm) IPMC film buckles and twists under it own weight.

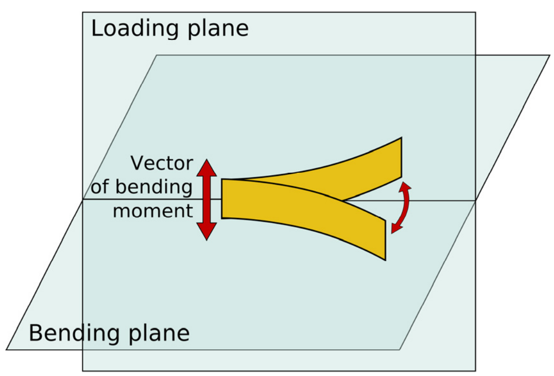


Fig.2. The planes of bending and loading when IPMC is used to propel a swimming robot.

The surface modification approach was suggested by anecdotal evidence [12, p.178] of increased bending amplitude of IPMCs after and initial "working" phase. Our own analysis of "just made" and "well worked" IPMC actuators (Fig. 3) shows that the worked samples have directional cracks on the surface of the metal, which are, likely, created by repeated bending.

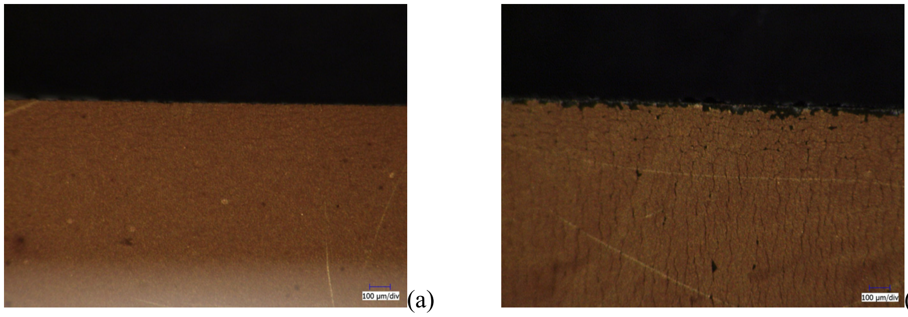

(a) (b)

Fig.3. Optical microscope images of the electrode surface of a “just made” (a) and “well worked” (b) IPMC.

These observations lead us to the idea of artificially introducing anisotropy in the IPMC during its manufacturing, so that it has a “preferred” bending direction. Two methods to introduce such anisotropy on the surface were tried – the first one by artificially introducing cracks after each electrode plating cycle, and the second, by introducing directional surface roughness on the polymer surface before plating. The directional roughness approach resulted in more than double increase of the bending amplitude.

2. MANUFACTURING METHOD

The IPMCs were manufactured by the well established chemical plating method by ion impregnation and consecutive reduction [13, 14]. In this method the ionic polymer membrane is impregnated with metal ions in a metal salt solution. Later, reducing agent is introduced and the metal ions precipitate on the surface of the membrane to form the electrodes.

One of the commercially available ionic polymer membranes most commonly used for IPMC actuators is Nafion® from DuPont. Nafion 1110 membrane with thickness of 250 μm in dry condition was used in the present study. The initial step in the preparation of the Nafion membrane for chemical plating is to roughen it by sandblasting. This isotropic roughening facilitates the formation of fractal-like electrode structure inside the polymer membrane. Fractal electrodes have larger surface area. This increases the capacitance and improves the bending response of the IPMC.

One commonly used metal for the electrodes is platinum, however, gold electrodes are softer, stable in acid, more conductive than platinum and less electro-chemically active [15]. For this reason, gold was selected in this study. In the case of the gold-plating on the polymer membrane, the impregnation-reduction cycle is usually repeated several times to have deep penetration of the electrodes inside the polymer. Seven plating cycles were done in this study. Further details of this particular coating process can be found elsewhere [15].

In the present study we applied two different modifications of the above described manufacturing process in order to obtain an IPMC actuator with “preferred” bending direction. The first approach was to introduce as a part of the manufacturing process cracks on the surface of the electrode, similar to the ones naturally formed by “working” the IPMC. The cracks on the electrode surface were formed by tightly bending and rolling the IPMC after each plating cycle (Fig. 4). As in the original process, the Nafion surface was prepared by sandblasting.

The second approach to create a “preferred” bending direction of the IPMC was to substitute the sandblasting of the polymer surface with directional roughening by sandpaper. Sandpaper with grain size No. 240 was used for roughening the Nafion surface prior to chemical plating. Fig. 5 shows the sandblasted surface and the roughened surface. Optical micrographs of the surfaces of the manufactured IPMCs are shown in Fig. 6 and the specimens are shown schematically in Fig. 7.

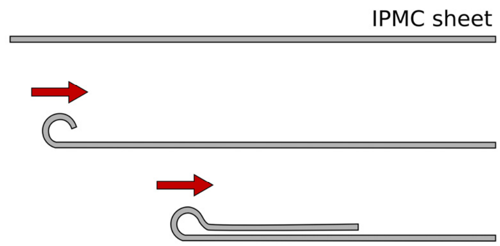
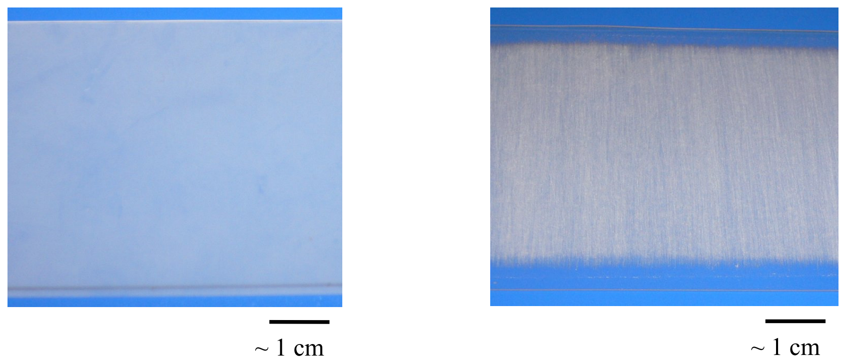
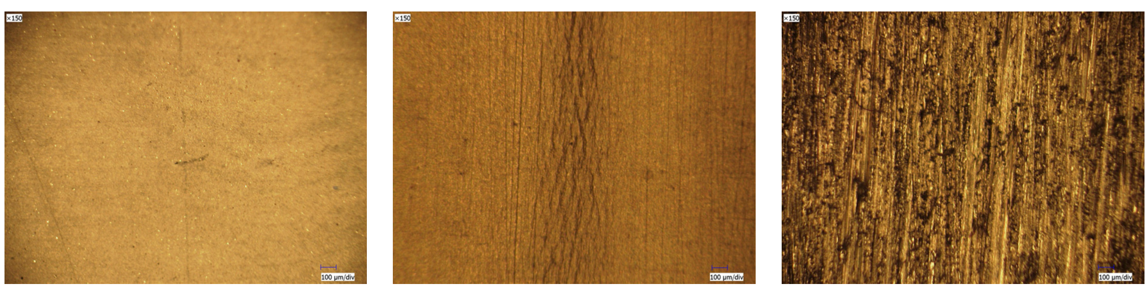


Fig.4. Forming cracks on the electrode surface by tightly bending and rolling the IPMC.



(a) (b)

Fig.5. Nafion 1110 (250 µm thickness) surface after (a) sandblasting, and (b) directional roughening by sandpaper with grain size 240.



(a) (b) (c)

Fig.6. Optical micrographs of different electrode surfaces of IPMCs. (a) gold plating over sandblasted Nafion surface; (b) artificially introduced mechanical cracks after each plating cycle on sandblasted Nafion surface; (c) gold plating over directionally roughened Nafion surface.

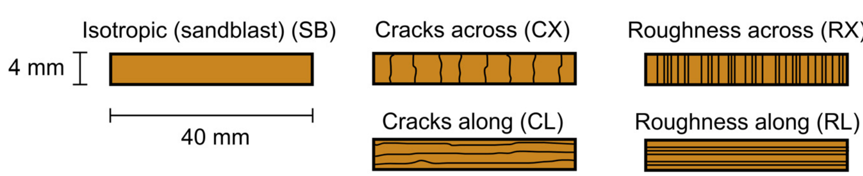


Fig.7. Schematic drawing of the 5 IPMC specimens used in the tests.

After the gold electrodes were plated on the Nafion surface, the test specimens were cut out in rectangular strips with size 40 x 4 mm (Fig.7). Five different specimens were prepared – one reference specimen with isotropic surface prepared by the traditional method after sandblasting of the Nafion (SB); two specimens with artificially made cracks on the electrode surfaces after each gold-plating cycle on sandblasted Nafion – one with cracks across its length (CX) and another one with cracks along it (CL); finally two specimens with directionally roughened by sandpaper surface (instead of sandblasted) – one with grooves across the length (RX) and another one with grooves along it (RL). The thickness of all the specimens in their water swelled state was measured by micrometer screw gauge and it was about 285 μm, with deviations less than 10 μm depending on measurement location and specimen.

3. EXPERIMENT

The forces produced by IPMC actuators are small, in the range of a few miliNewtons, and this necessitates the use of a non-contact measurement method for the bending response. Laser displacement meters have been used successfully in the past [16] and we apply similar methodology. The principle of operation of the laser displacement meter is briefly described. When the laser beam is projected onto the target surface, the reflected light is observed by a CCD sensor. When the distance between the sensor and the observed surface is changed, the location of the reflected spot on the CCD sensor changes and the displacement can be measured. In our tests we used laser displacement meter LK-G 155, manufactured by KEYENCE.

When the IPMC actuators are taken out of the water, they are still operable until they dry out completely. Water content and humidity in the environment affect the response of IPMCs. Unfortunately, the drying out process is not easily controlled in room conditions, so we have chosen to compare the bending response of our specimens in water. This adds some other complexities in measuring the bending response, which will be briefly discussed.

The schematic diagram of the measurement system is shown in Fig.8. The IPMC actuator samples are held vertically under water with temperature 25°C. They were driven from PC DAC-board through a potentiostat by sinusoidal voltage signal with amplitude 1 V and frequency 0.5 Hz. The laser displacement sensor is placed so that the laser beam is perpendicular to the wall of the transparent container and projects a spot at 10 mm from the lower edge of the specimen. Complexities arise, because of the refraction, which occurs at the water-container and container-air interface. In the following brief theoretical consideration we neglect the effects of the transparent plastic wall of the container and only consider the water-air interface.

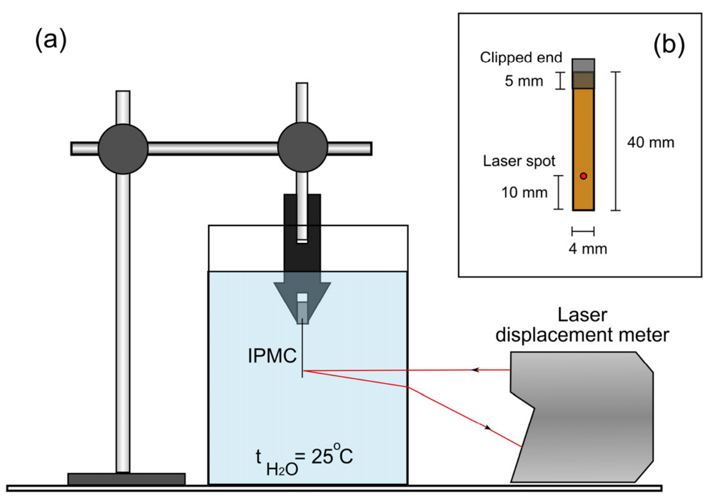


Fig.8. Experimental setup - (a) general view; (b) details of IPMC specimen fixing and measurement spot location.

Because the laser beam is perpendicular to the wall of the container it is not refracted, but continues straight to the target surface (Fig. 9). Refraction, however, takes place when the reflected light beam reaches the water-air interface (container wall is assumed to have negligible effects). According to Snell's law:

$$n_i \sin\theta_i = n_r \sin\theta_r \tag{1}$$

where n_i, n_r are the refraction indexes of the media in which incident and refracted rays travel; θ_i, θ_r are the angles of incidence and refraction.

The incident ray in our case travels in water, which has refraction coefficient $n_i = 1.333$ and is refracted in air, which has refraction coefficient $n_r = 1.003$.

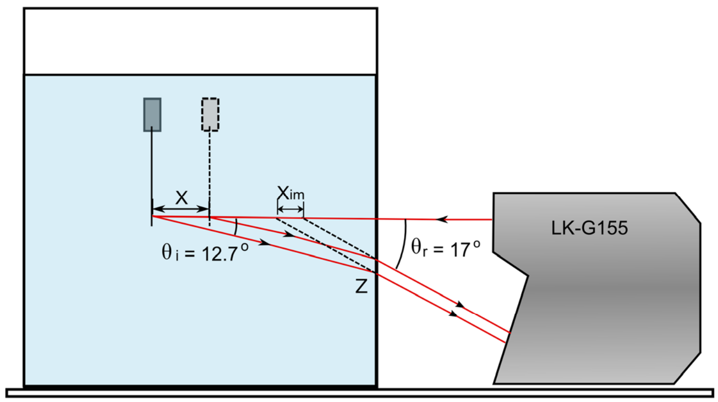


Fig.9. Refraction at the boundary between water and air (details are in the text).

The particular laser displacement meter that we used (KEYENCE, LK-G155) measures displacement from the rays reflected at an angle of 17°. This means that only rays refracted at the interface at 17° will be picked by the sensor and from Snell's law we can determine the angle of incidence of those rays:

$$\sin\theta_i = \frac{n_r}{n_i}\sin(17°) \tag{2}$$

$$\theta_i = 12.7° \tag{3}$$

With this angle we can calculate the ratio of the real displacement X to the image of the displacement X_{im} as seen by the CCD sensor. From Fig. 9. it can be seen that the projection at the interface Z can be expressed as:

$$\begin{aligned} Z &= X \tan\theta_i \\ Z &= X_{im} \tan\theta_r \end{aligned} \tag{4}$$

Then,

$$k = \frac{X}{X_{im}} = \frac{\tan\theta_r}{\tan\theta_i} = 1.356 \tag{5}$$

This value was verified experimentally by moving the target surface to and away from the sensor by calibrated micrometer screws as shown in Fig. 9. Experimentally obtained values were in the range between 1.326 and 1.362, which confirms that there is no significant error if the effect of the container wall is neglected. In all the consecutive calculations the value of k = 1.35 will be used as a compromise value from the theoretical considerations and the experimental data, without introducing significant errors (less than 2 %).

4. RESULTS AND DISCUSSION

The deflection of the isotropic sample under 0.5 Hz 1 V sine voltage excitation is shown in Fig. 10. The amplitude grows for the first few cycles until it reaches a maximum and then gradually drops. Similar raw data were obtained for all the samples. The maximum deflection is obtained as the sum of largest positive and largest negative deflection. The maximum deflection from the signal in Fig. 10 is shown together with the maximum deflection of the other samples in Fig. 11.

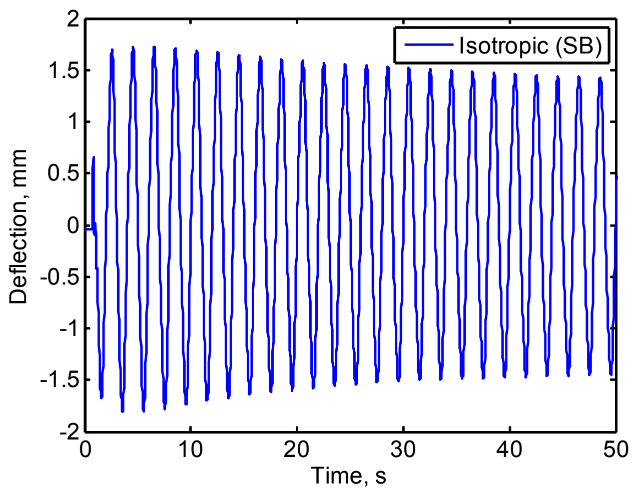


Fig.10. Deflection of IPMC (gold plated Nafion 1110, 40 x 4 mm, 285 μm thickness) with isotropic surface under excitation by 1 V 0.5 Hz sine voltage.

In all cases the maximum deflection initially grows for the first few cycles and then gradually drops until a stable level is reached. The deflection of the reference sample with sandblast Nafion surface was smallest, while the specimen with roughness grooves across the length of the IPMC showed the largest displacement. After about 75 cycles the maximum deflection changes very little and at this point the amplitudes normalized to the isotropic IPMC amplitude are compared in Fig. 12. Roughening the surface of Nafion with grooves across the length of the IPMC resulted in more than 2.1 times increase of the bending amplitude. Specimens with roughness grooves and cracks across the IPMC length bent more than specimens with grooves and cracks along it. Roughness grooves and artificially made cracks in the direction in which cracks form naturally, facilitate higher bending amplitude. Even if the direction of the grooves and cracks were perpendicular to the direction of natural cracks, the surface treatment improved the bending response of IPMCs, compared to the standard sandblast surface.

At present we do not have clear understanding about the reason for such an increase in bending amplitude, but it may be caused by a change in mechanical properties, electrical properties or both. At present investigations in this regard are under way and from the preliminary results it seems that reduction of IPMC stiffness in the direction of bending plays an important role. At the same time the stiffness of the 285 μm thick IPMC samples in the plane of loading is much improved compared to thin IPMC films, and they can easily sustain their own weight without buckling and twisting (Fig. 13).

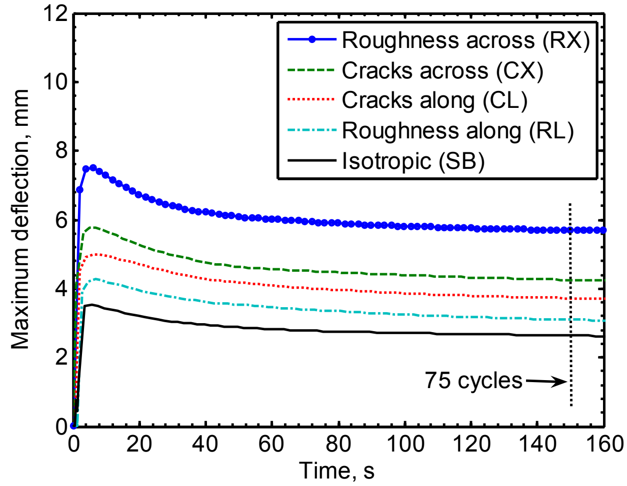


Fig.11. Maximum deflection of IPMC (gold plated Nafion 1110, 40 x 4 mm, 285 µm thickness) with different surface modifications under excitation by 1 V 0.5 Hz sine voltage.

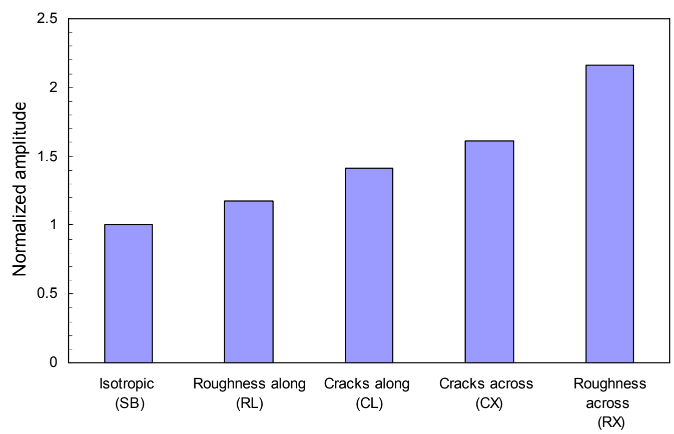


Fig.12. Normalized amplitude comparison for IPMC (gold plated Nafion 1110, 40 x 4 mm, 285 µm thickness) with different surface modifications.

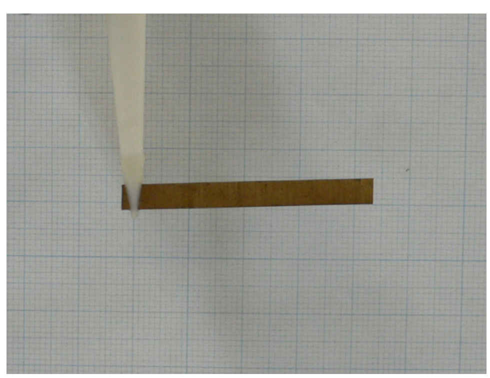


Fig.13. Thick (285 µm) IPMC with roughened surface is sufficiently rigid in the plane of loading and can easily sustain its own weight.

6. CONCLUSIONS

In order to enhance the bending response of ionic polymer-metal composite (IPMC) actuators under the limitations of driving voltage below the onset of water electrolysis at about 1.2 V and at the same time without compromising rigidity in the loading plane perpendicular to the plane of bending, we applied two different surface modification techniques to create a “preferred” bending direction.

Introduction of anisotropic roughness with grooves across the length of the actuator improved the bending response by a factor of 2.1. Artificially introduced cracks on the electrodes in the direction, in which cracks form naturally by bending, which is across the length of the actuator, improved bending response by a factor of 1.6.

These results demonstrate that anisotropic surface modification is an effective method to create a preferred bending direction and enhance the bending response of IPMC actuators when driving voltage cannot be increased and it is a method, which does not compromise the rigidity of the IPMC when it is loaded perpendicularly to the bending plane.

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