Research article

Ionic polymer-metal composites (IPMCs) and ionic polymer-polymer composites (IP^{2}Cs): Effects of electrode on mechanical, thermal and electromechanical behaviour

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Abstract: Electro-active polymers (EAPs) are soft polymers that develop mechanical strain if subjected to electrical stimuli or, on the contrary, produce voltages if mechanically deformed. Their discovery has led to take into account their possible use as sensor-actuator for both bio-mimetic applications and traditional robotics. Ionic polymer-metal composites (IPMCs) and ionic polymer-polymer composites (IP^{2}Cs) belong to EAPs. Both of them are fabricated starting from an ionic polymer (typically Nafion®117) but while in IPMCs the electrode is based on a metal (Ag, Au or Pt), IP^{2}Cs are all-organic devices: in fact a conducting polymer (e.g., poly(3,4-ethylendioxytiophene)-polystyrenesulfonate, PEDOT/PSS) is used as the electrode. In this work, a comparison has been done among the fabrication processes and the mechanical, thermal and electromechanical behaviour of IPMCs and IP^{2}Cs. The objective is to investigate the influence of the kind of electrode on the final properties of the devices, taking, also, into account the effect of different solvents, used for realizing the actuation process (H_2O or Ethylene Glycol). Reported results show that the performance of the obtained devices are function of manufacture parameters, the kind of electrode and solvent; consequently, taking into account the possible application, it is possible to choose the device that better meets specific requirements.

Keywords: electroactive polymers (EAPs); ionic polymer-metal composites (IPMCs); ionic polymer-polymer composites (IP^{2}Cs); thermal and mechanical analyses; electromechanical

characterization

1. Introduction

In recent years, much interest has been devoted to the research of innovative materials for the development of flexible electromechanical transducers and electroactive polymers (EAPs) have been extensively investigated because of their flexibility and lightness. Ionic Polymer-Metal Composites (IPMCs) are classified among EAPs [1–13]. They have been proposed for applications in various fields (soft robotic actuators and artificial muscles, dynamic sensors in the micro to macro-size range) due to the fact that they are light, soft, resilient, flexible, can be cut into any shape and size and are envisaged for biomedical applications. IPMCs show large bending deformation under low driving voltages, due to their capabilities to exhibit sensing and actuation properties; in fact, they bend if an electric field is applied across their thickness and, vice versa, they generate an electric reaction when subjected to a mechanical deformation. IPMCs (Figure 1) consist of an ionic polymer membrane (e.g., Nafion®117), metallized on both sides with a noble metal (e.g., silver (Ag), gold (Au) or platinum (Pt)). These metals are characterized by high cost and require complex deposition techniques in order to obtain the electrodes. For these reasons, a novel class of all-organic electroactive polymers, called Ionic Polymer-Polymer Composites (IP^{2}Cs) have been fabricated realizing the electrodes by organic conductors (e.g., polyanyline, polypyrrole, poly(3,4-ethylendioxytiophene)-polystyrenesulfonate (PEDOT/PSS)), (Figure 1) [14–19]: they can operate, as IPMCs, both as electromechanical actuators and as sensors. This new kind of systems has a huge potential because develops flexible substrates by low production costs and maintains electromechanical coupling capability, low required voltage, high compliance, lightness and softness.

While in IPMC the electro-mechanical transduction capability is due only to the migration inside the Nafion membrane of mobile ions (H_3O^+) and of the cation hydration shell water molecules (due to hydration of the sample) (Figure 1b), in IP^{2}C, besides to these phenomena, the presence of the conductive polymer based electrodes, that can deform during red-ox reactions, can contribute to the electro-mechanical transduction. In both systems device actuation is obtained by the application of an electric field to the electrodes that mainly generates the motion of free cations through the membrane.

In this work, the authors compare the fabrication processes and properties of IPMCs and IP^{2}Cs, manufactured starting from Nafion®117 as the ionic polymer. While in IPMCs the electrode is based on Pt as metal, in IP^{2}Cs, the electrode element has been obtained directly polymerizing a conducting polymer (PEDOT/PSS) on Nafion®117. At present, the prevailing method to fabricate IPMCs requires depositing noble metals onto a cation-exchange film through chemical deposition technology in an electroless plating process. Moreover to improve the performances, additional post-processes have been utilized such as several cycles of Pt electroless plating [3] and using of dispersing agents [2,4,12,20–24]. In fact, an increase in the number of Pt electroless plating steps determines an increase in the thickness of the electrode and it is known that the amount of particles and the interfacial area increase proportionally to the thickness of the electrode. A larger conductor–polymer interface area influences the capacitance of the electric double layer and, adding more particles to the electrode, the performance of the device increases. Regarding the effect of dispersing agents, it is known that, to achieve high efficiency for IPMCs, it is necessary to reduce or

eliminate the water leakage out of the surface electrode so water transport within the IPMC can be more effectively utilized for actuation. The decreasing of water contained in the polymer membrane is due to leakage out of the electrode's porous surface and electrolysis and, to avoid this loss, it is necessary to obtain a uniform surface of the electrode. Due to a platinum particles coagulation process, in the IPMC, the surface of the electrode is not uniform but the use of dispersing agents, (introduced during chemical reduction processes) alleviates this phenomenon, enhancing the dispersion of platinum particles within the ionic polymer, controlling their size and reducing coagulation. By this procedure a better metallic particle dispersion in the polymer (the better the distribution, the lower the surface resistance) with smaller average particle sizes and more uniform distribution can be obtained. Obviously, if the distribution is uniform, it will be more difficult for water to pass through the electrode layer and the water leakage out of the surface electrode will be reduced.

Relatively to manufacture of IP^{2}Cs, poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS) has been used as organic conductor, because it is one of the best known conducting polymers. In fact, it shows excellent electrical conductivity as well as processability. At first, drop-casting deposition techniques were used starting from Nafion$^®$117 using different commercial formulations of PEDOT/PSS as electrode material (CLEVIOS ™ PH500, CLEVIOS ™ PHCV4, CLEVIOS ™ PH510, all by Baytron$^®$) [17]. As for IPMCs, problems raised both because of loss of water by decomposition and evaporation when these devices operated in air [2,4]. The problem could be overcome rehydrating the device. Unfortunately, in IP^{2}Cs manufactured by this technique, the organic electrodes delaminated and degraded during the hydration with the solvent. In a previous work [19], to improve the adhesion between Nafion$^®$117 and conducting polymer and avoid the degradation of the electrode during the rehydration, the organic conducting polymer (PEDOT/PSS) was directly polymerized on the Nafion$^®$117 surface by oxidative polymerization of the monomer 3,4-ethylendioxytiophene, EDOT.

As already mentioned, the actuation behaviour of IPMCs and IP^{2}Cs is driven by the solvent movement inside the membrane [25] and, consequently, it is fundamental the electrochemical stability of the solvent. Water is widely utilized as inner solvent but during the applications it can evaporate or decompose in hydrogen and oxygen due to electrolysis process when applied voltages are higher than 1.3 V. Both phenomena result in a deterioration of the actuation performances. This problem can be overcome by using solvents other than water as, e.g., Ethylene Glycol (EG) [26–29]: in fact, it consists of polar molecules, like water, but has a high boiling point (197.6 ℃) and can be subjected to relatively high voltages, without electrolysis. Consequently, the devices can show higher durability than the ones with water, even if the actuation response can be slower due to higher viscosity (16.1×10^{-3} Pa s) and lower conductivity (1.07 mS cm^{-1}) of EG with respect of water (1.00×10^{-3} Pa s and 5.5 mS cm^{-1}). Moreover, it is known that an improvement of the properties of PEDOT/PSS can be obtained by chemical treatment that involves the addition of co-solvent. It has been reported [30] that the strong electron-phonon coupling of PEDOT/PSS, that results in a low carrier mobility at room temperature, can be modified using EG as co-solvent. The incorporation of EG in PEDOT/PSS makes it possible to decouple electrons and phonons, enhancing the electrical properties of the conducting polymer. It can be argued therefore that by using EG in IP^{2}Cs, instead of water, a beneficial effect on the actuation properties of the devices can be obtained.

All the obtained IPMCs and IP^{2}Cs, manufactured using different solvents (H$_2$O and EG), have been characterized by scanning electron microscopy (SEM), dynamical mechanical (DMA) and

thermogravimetric (TGA) analyses and electromechanically tested as actuators. A study of structure-property relationships in these devices has been done in function of the different kind of electrode and solvent and, finally, a comparison of different advantages and disadvantages in the application of IPMCs and IP^{2}Cs concludes the work.

The paper is organized as follows: in Materials and Method section, we present IPMC and IP^{2}C fabrication procedures and the techniques adopted for their morphological, dynamical mechanical, thermogravimetric and electromechanical characterization. In the Results and discussion section, we comment and compare the obtained data and analyse advantages and disadvantages in the use of IPMCs and IP^{2}Cs. The last section is left for conclusions.
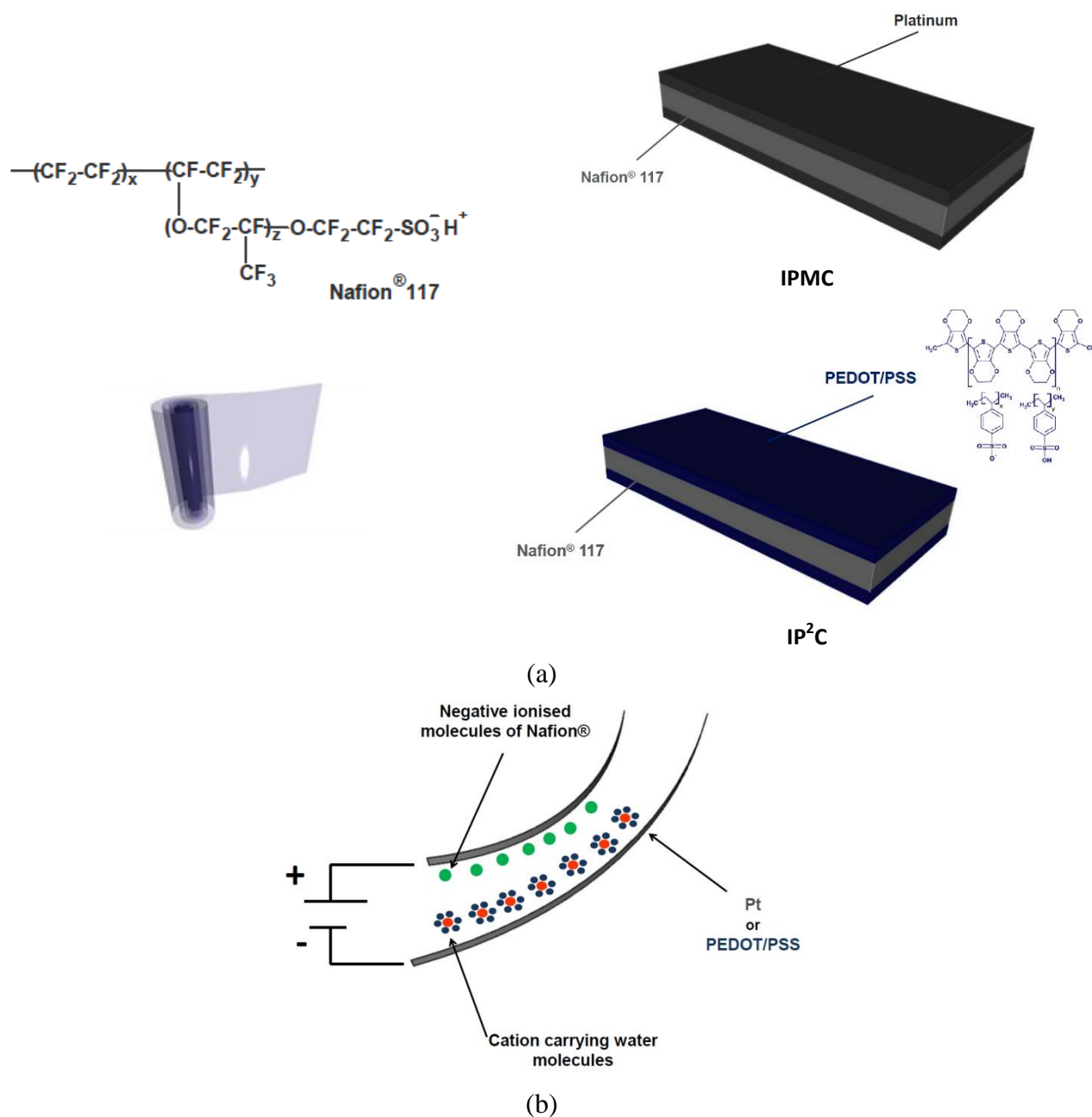

(a)

(b)

Figure 1. IPMC and IP^{2}C fabrication technique (a) and interaction of charges within the IPMC and IP^{2}C (b).

2. Materials and Method

2.1. Membrane Preparation

All devices have been realized starting from Nafion®117 (a fluorocarbon membrane (thickness 178 μm), produced by Dupont and distributed by Sigma-Aldrich Group) (Figure 1a). All other reagents are commercial materials (Alfa Aesar Company) and were used without purification. A scheme of IPMC and IP²C fabrications is reported in Figure 1a. To manufacture IPMCs, the experimental procedure is well documented [1–4,12,13] and includes roughening and cleaning of the Nafion®film, ion-exchange with tetrammineplatinum chloride ($Pt(NH_3)_4Cl_2$) and double chemical reduction (respectively a primary plating by sodium borohydride ($NaBH_4$) and a secondary plating by hydroxylamine hydrochloride, NH_2OH-HCl, and hydrazine, NH_2NH_2). In particular, IPMCs have been manufactured in presence, as dispersing agent, of polyvinylpyrrolidone (PVP10, $M_w = 10000$, 0.001 M, added either during the primary and the secondary plating) and by 3 sequential primary platings (adsorption for 20 hours in $Pt(NH_3)_4Cl_2$ solution/reduction by $NaBH_4$). The formation of reduced platinum resulted in metallic grey layers deposited on both surfaces of the Nafion® membrane.

Regarding fabrication of IP²Cs, a typical film deposition experiment [19,31,32,33] is based on the formation of the organic conductor electrode by polymerization in situ (1 h) of PEDOT on Nafion®117 film starting from 3,4-ethylendioxytiophene (EDOT) and sodium polystyrene sulfonate (NaPSS, added to improve the solubility of EDOT). Upon addition of $Fe(NO_3)_3$ $9H_2O$, EDOT polymerized leading to a dark blue layer deposited on both sides of the membrane piece. The membrane, rinsed with double distilled water, has been boiled in H_2SO_4 1 M (1 h), to perform the exchange of Fe^{3+} with H_3O^+ ions, and then in H_2O (1 h). In order to obtain IPMC and IP²C with EG as solvent, water has been removed drying the devices at 100 ℃ for 24 h, then the devices have been soaked overnight in a beaker containing EG and, at last, heated to 60 ℃ for 1 h. All manufactured samples are listed in Table 1 (as references, pure Nafion®117 membranes, soaked with the H_2O and EG, have been used).

Table 1. Manufactured samples.

	Solvent	Sample code
Nafion®117	H_2O	Nafion®117/H_2O
	EG	Nafion®117/EG
IP²C(1 h)	H_2O	IP²C/1 h/H_2O
	EG	IP²C/1 h/EG
IPMC	H_2O	IPMC/H_2O
	EG	IPMC/EG

2.2. Characterization

The solvent uptake level of the films, determined to find out the water absorbing capacity, has been calculated by the difference between the weight of the swollen membrane (W_1) and the dried

sample (100 ℃ for 24 h) (W_0) using the following equation:

$$\text{Solvent uptake (\%)} = [(W_1 - W_0)/W_0] \times 100\% \qquad (1)$$

SEM (Scanning Electron Microscopy) micrographs have been obtained using a Cambridge 90 instrument equipped with an energy dispersive X-ray microanalysis (EDX) facility. The surface morphology and cross-sectional view (obtained on frozen-fractured samples) of the electrode layers (PEDOT/PSS in IP^{2}C and Pt in IPMC) have been examined. The dynamical mechanical analyses (DMA) of all samples have been performed by a 2000 TA DMA produced by Triton Technology Ltd. The frequency dependence of the modulus of the membranes has been evaluated, in tension mode, by applying a sinusoidal force in the range 0.1–100 Hz (T = 25 ℃). All the tested specimens have rectangular shape. The analyses have been performed on membranes fully solvent saturated. Solvent on the surfaces of specimens has been wiped off with absorbent paper to remove the adhering excess before the measurements.

Thermogravimetric analyses (TGA) have been carried out on a Shimadzu model DTG-60 instrument. TGA curves have been recorded at a heating rate of 10 ℃·min^{-1} under a nitrogen atmosphere (20 ml·min^{-1}) from 35 to 700 ℃, in hydrated conditions. Analyzed sample mass varied between 8.0 and 11.0 mg.

To compare and analyze the device performances as actuators, the samples have been cut in strips of size 2.6 cm × 0.5 cm; a swept signal of amplitude 2 V and a growing frequency (from 0.1 to 50 Hz) have been applied through the measurement setup. Absorbed current and the sample free deflection have been measured through a conditioning circuit and by means of a laser proximity sensor, respectively. The Bode diagrams of sample displacement and sample resonance frequency have been evaluated.

3. Results and Discussion

In the obtained devices, Nafion[®]117 has been used as base material, while the electrode has been realized by metallic platinum in IPMC and PEDOT/PSS in IP^{2}Cs (by polymerization *in situ*). Regarding the manufacturing procedures, the one required to produce IPMC is complex, long and expensive while for IP^{2}C it is easier, faster and cheaper. In fact, only 1 day is required for fabricating IP^{2}C instead of 5 days necessary for IPMC; moreover the manufacturing cost is 0.37 €/cm^2 for IP^{2}C against 7.55 €/cm^2 for IPMC. The adhesion of the electrode on Nafion matrix it is very good in both devices: the electrodes adhere strongly giving a grey metallic layer of platinum in IPMC and a blue-black appearance of PEDOT/PSS in IP^{2}C, respectively. The very good adhesion has been confirmed by the possibility of rehydrating both the devices after their use without any evidence of degradation. In the case of IPMC, platinum particles, deposited on both the surfaces of Nafion[®]117, fill some parts of the membrane channels and the measured electrode layer is about 15–20 μm [2,27]. In the case of IP^{2}Cs, probably, the sulfonic acid groups of Nafion[®]117 may serve as counter-ions in the PEDOT polymerization process so that the polymerization inside the Nafion membrane, also in this case, cannot be excluded [33]; the film is uniform and compact and the thickness is about 8 μm (Figure 2).

It is known that the actuation in IPMCs and IP^{2}Cs is driven by the migration of solvent and ions. In Figure 3, the solvent uptake of the devices with different inner solvent (calculated as weight percentage) is reported. Relatively to the influence of electrode, in IPMCs, the layer of platinum is

thicker than PEDOT/PSS in IP^{2}Cs but, as it is possible to observe in Figure 2, the surface shows some fractures, consequently the devices can absorb an higher quantity of solvent. Regarding the kind of solvent, due to a strong chemical interaction between Nafion[®]117 and EG [26,27] and to the high molecular weight of EG, it is possible to observe that IPMCs and IP^{2}Cs absorb more EG than H_2O.
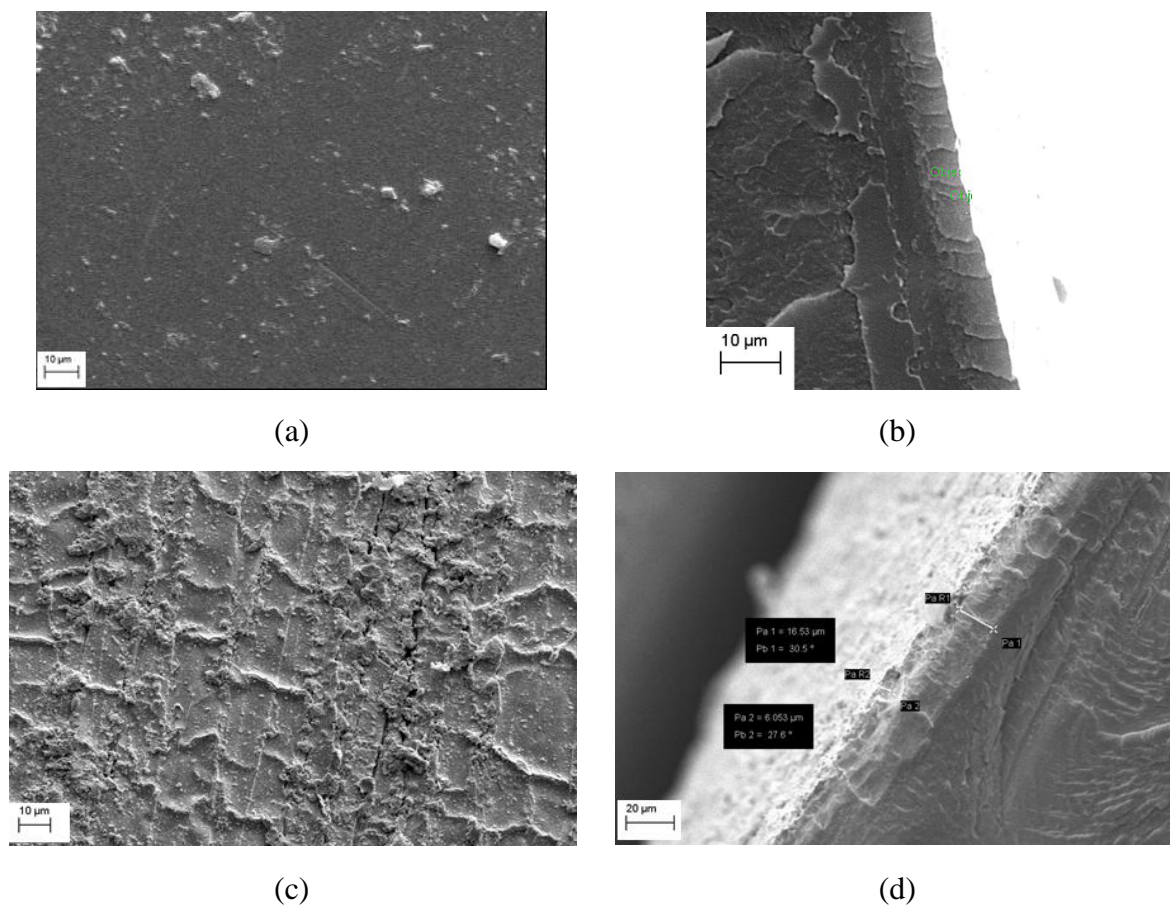

(a)	(b)
(c)	(d)

Figure 2. SEM images of surface and cross-sectional view of IP^{2}C/1h (a, b) and IPMC (c, d).
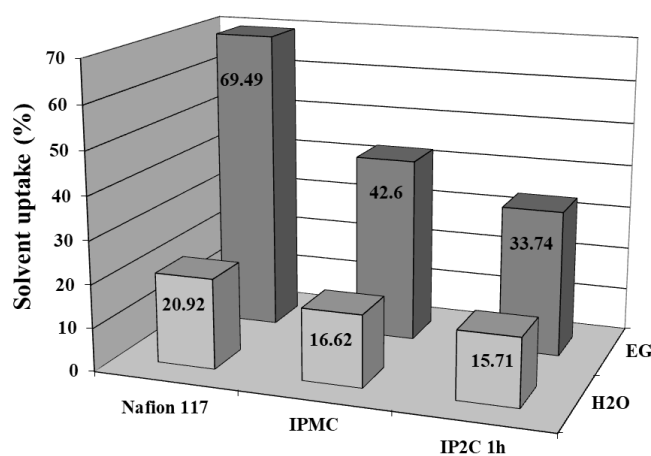

Figure 3. Solvent uptake of Nafion[®]117, IPMC and IP^{2}C with different inner solvent (H_2O and EG).

When such composite are investigated TGA and young modulus determination are routinely performed. In fact TGA can give information on the amount and nature of the solvent and on the degradation step of the membrane. Also, the low temperature region of the TGA scan can give information on the capability of the device in retaining the solvent because of the porous nature of the electrodes [34,35]. The DMA, through the modulus determination can give insight on the electromechanical transduction performance of the composite [36].

In TGA, the sample is heated in a furnace and the weight loss is measured as a function of the temperature. The thermal stability of IP^{2}C and IPMC, in H_2O and EG as solvent, has been studied. The results have been reported as percentage of undegraded sample and derivative weight loss (DrTGA) as function of temperature. Such an investigation allows for obtaining some information relatively to thermal stability of the devices and, by comparison with the Nafion$^®$117, to the effect that the kind of electrode determines for what concerns the rate of solvent loss from the device as the temperature increases. As shown in Figure 4, in Nafion$^®$117/H_2O membrane it is possible to individuate different step relative to mass loss: the first (range 25–290 ℃) can be attributed mainly to the loss of free water or physically adsorbed water; the second (range 290–400 ℃) is associated with a desulfonation process ($H_2O_{(g)}$, $SO_{2(g)}$ and $CO_{2(g)}$ are liberated during the thermolysis); the third stage (range 400–470 ℃) is related to side-chain decomposition and, at last (470–560 ℃), the one due to PTFE backbone decomposition (with HF, SiF_4 and COF_2, typical gases liberated) [19,37,38,39]. In IP^{2}C and IPMC, the electrode (PEDOT/PSS and platinum, respectively) exerts a barrier effect which slows the loss of water thereby extending the operating temperatures of the device and determining an increase of the "thermal stability" of the system. Moreover, regarding the degradation processes, the obtained results show that the processes of thermal degradation of the Nafion$^®$117 overlap with those of the conductive polymer PEDOT/PSS in IP^{2}C and of platinum in IPMC.

In particular, when H_2O is used as solvent, in the devices (Figure 4a) is firstly noted that, on increasing the temperature virgin Nafion$^®$117 film shows a progressive increase in the rate of water loss (that reaches the maximum speed at about 70 ℃). On the contrary, IP^{2}C and IPMC loss the solvent with a constant speed throughout the temperature range of 25–290 ℃ (no peak in DrTG). These results can be interpreted in terms of electrode uniformity and compactness. Conductive polymer in IP^{2}C and platinum in IPMC produce electrodes that more efficiently act as a barrier, making more difficult for water to pass through (granular damming effect). Consequently, the rate of the water leakage out the surface electrode is reduced. Relatively to DrTGA data, it is possible to observe that, in IP^{2}Cs, in the range 290–400 ℃ the decomposition is associated with a desulfonation process and interests both sulfonic functions of Nafion$^®$117 and PEDOT/PSS. In IPMC, the presence of platinum instead of PEDOT/PSS, determines a higher stability of the device probably because the desulfonation process is limited only to sulfonic function of Nafion$^®$117. At temperature higher than 550 ℃ the metallic layer in IPMC still acts as a barrier for degradation products.

In Figure 4b, TGA and DTG of IPMC and IP^{2}Cs are reported when EG is used as solvent. In the range 100–200 ℃, due to the extremely hygroscopic nature of EG and to the mass loss of free or physically adsorbed EG, it is possible to observe a large weight loss in Nafion$^®$117/EG, IPMC/EG and IP^{2}C 1 h/EG with respect to ones with H_2O (Figure 4a). As can be observed from the DrTG of the devices containing EG, there are two steps in solvent loss: the first is relate to the hygroscopically adsorbed water and shows a maximum rate of loss at about 90 ℃. The second, with a maximum rate of weight loss at about 150 ℃, it is relative to the EG loss.
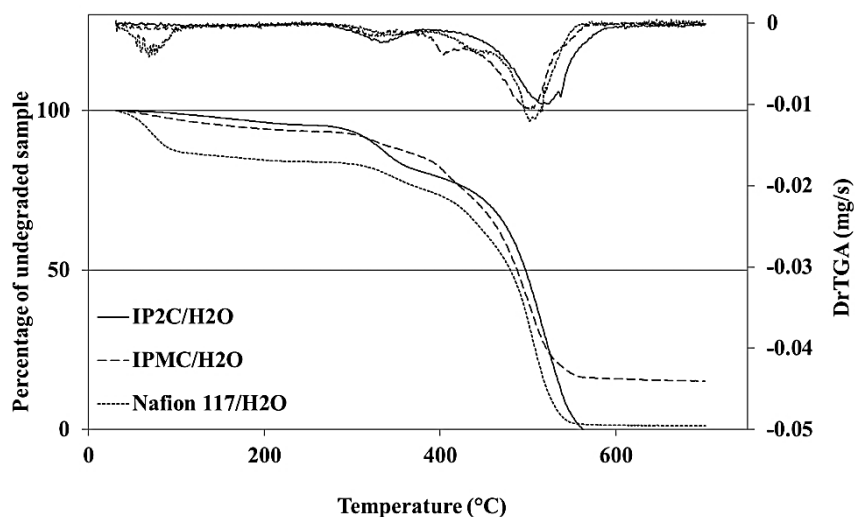
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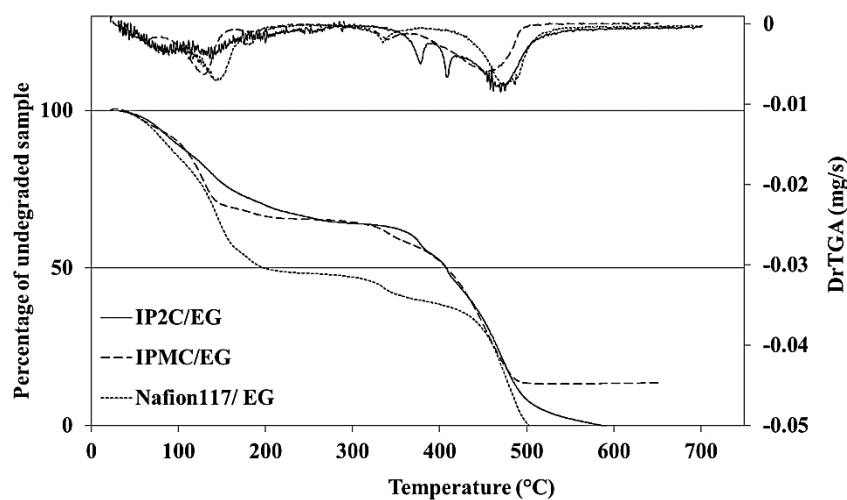
(b)

Figure 4. TGA and DrTGA of Nafion$^{®}$117, IP^{2}C/1 h and IPMC with H$_2$O (a) and EG (b) as solvent.

Regarding the dynamical mechanical analyses, in most cases, the moduli values measured by DMA do not agree well with that obtained from mechanical testing methods [40], so they are utilized only for screening the material properties for the purposes of research and optimization of processing conditions. In this work, the results relative to a native Nafion membrane (Young's modulus 0.09–0.25 GPa) are in good agreement with those reported in the literature [41–44]. For DMA measurements of the samples, the tension mount (particularly useful for fibres, elastomers and films) has been used and a sinusoidal tensile force has been applied to the rectangular samples in the range from 0.1 to 100 Hz, at a working temperature of 25 °C, in hydrated condition. DMA measures stiffness and damping, so measurements of storage modulus (E'), loss modulus (E'') and tan delta (tan $\delta = E''/E'$) have been obtained and compared to determine the influence of the different kind of electrode and solvent on the mechanical properties of IPMCs and IP^{2}Cs.

In Figure 5, a comparison of the frequency response of storage modulus in IP^{2}Cs and IPMCs in presence of H_2O and EG is reported using as reference Nafion®117 membrane. In all devices, the presence of the electrode (Pt in IPMC and PEDOT/PSS in IP^{2}C) determined an increase of the storage modulus respect to one of Nafion®117. In particularly, using H_2O as solvent, at low frequencies, IP^{2}C shows a higher storage modulus than IPMC, while at frequencies superior to 1 Hz an inversion is observed. Moreover, IPMC shows high storage and loss modulus simultaneously (generally the relationship is inverse) revealing both stiff and damping characteristics.
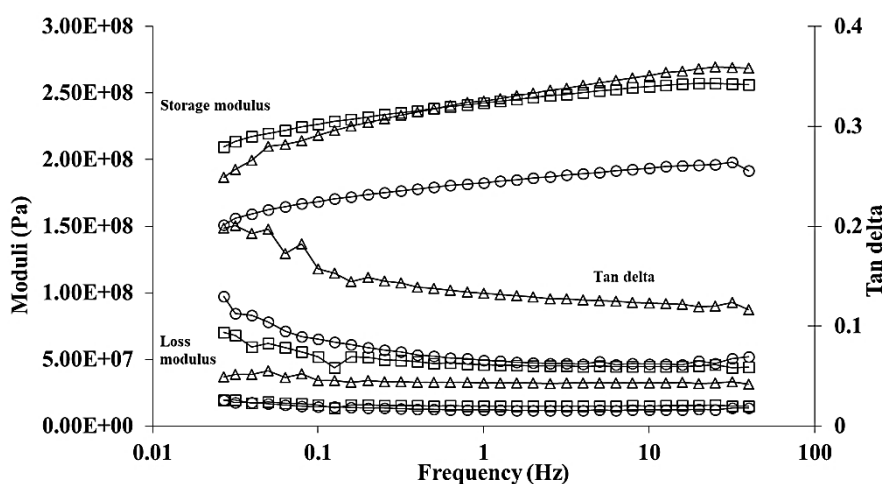
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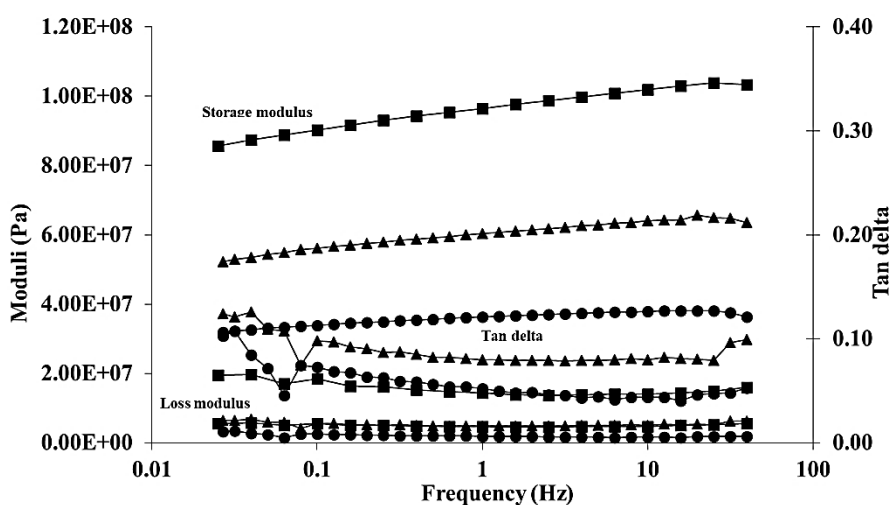
(b)

Figure 5. A comparison of storage modulus, loss modulus and tan delta for Nafion®117 (○), IP^{2}C/1 h (□) and IPMC (Δ) in H_2O (a) and EG (●, ■ and ▲ respectively) (b) as a function of frequency.

It is important to observe as the kind of solvent influences the mechanical properties of a device. In fact, a solvent acts as a plasticizer, with the consequence that the flexibility and elasticity of the film increase. The plasticizer works by reducing the interactions among the macromolecules and

thereby increasing chain mobility, which, in turn, leads to a softening or plasticization of the polymeric material. In our devices, the solvent present in the polymeric matrix interferes with chain-to-chain secondary bonding and the chains acquire greater mobility, increasing the free volume [45]. The samples with water as solvent exhibit higher storage modulus than those with EG. It is due to the fact that EG has a higher plasticizing effect with respect to H_2O. It depends on the fact that EG has a lower vapour pressure and therefore it has greater permanence in the Nafion membrane leading to a clear decrease of the storage modulus values for the devices with EG as solvent compared to the hydrates ones (Figure 5).

Regarding the electromechanical characterization of the devices, it has been carried out through the setups described in the methods section. The devices were tested in a cantilever configuration: one end has been fixed in a clamp fitted with copper foil electrodes to contact the conductive metal surface of the sample, while the other end is free in the case of deflection measurement. In particular, the free deflection, produced when a voltage signal has been imposed across the strip thickness, has been detected in order to compare the performances of the different devices as motion actuators. The obtained data are reported in Table 2.

Table 2. Obtained values of absorbed current, deformation and resonance frequency of IPMCs and IP^2Cs using different solvent (H_2O or EG).

	Absorbed current (A)	Maximum deformation (mm)	Resonance frequency (Hz)
IP^2C/H_2O	0.62	2.4	37.8
$IPMC/H_2O$	0.1	1.8	19.8
IP^2C/EG	0.05	0.1	42.1
$IPMC/EG$	0.08	0.7	17.95

When H_2O is used as solvent, IP^2C shows higher absorbed current than IPMC with a consequent higher deformation. It has to be noted that using H_2O as solvent, due to evaporation and electrolysis processes, the content of water inside the membranes changes during the measurements, generating a decreasing trend in the deformation thus changing the actuator performances (Figure 6). The consequence is that for the IP^2Cs and IPMC with H_2O as solvent, it is always necessary to re-hydrate the devices after the utilization.

In Figures 6 and 7, the Bode diagrams of the fabricated devices are reported: they permit to examine the frequency response of a system. In particular, by these diagrams, it is possible to determine the frequency at which the response amplitude is a relative maximum (resonance frequency). The diagrams report both the magnitude and the phase as a function of the investigated frequency range. From the diagrams and the data in Table 2 it is possible to observe that IP^2C are characterised, with respect to IPMC, by a larger value of the resonance frequency. Such a trend is shown by both water and EG based devices.
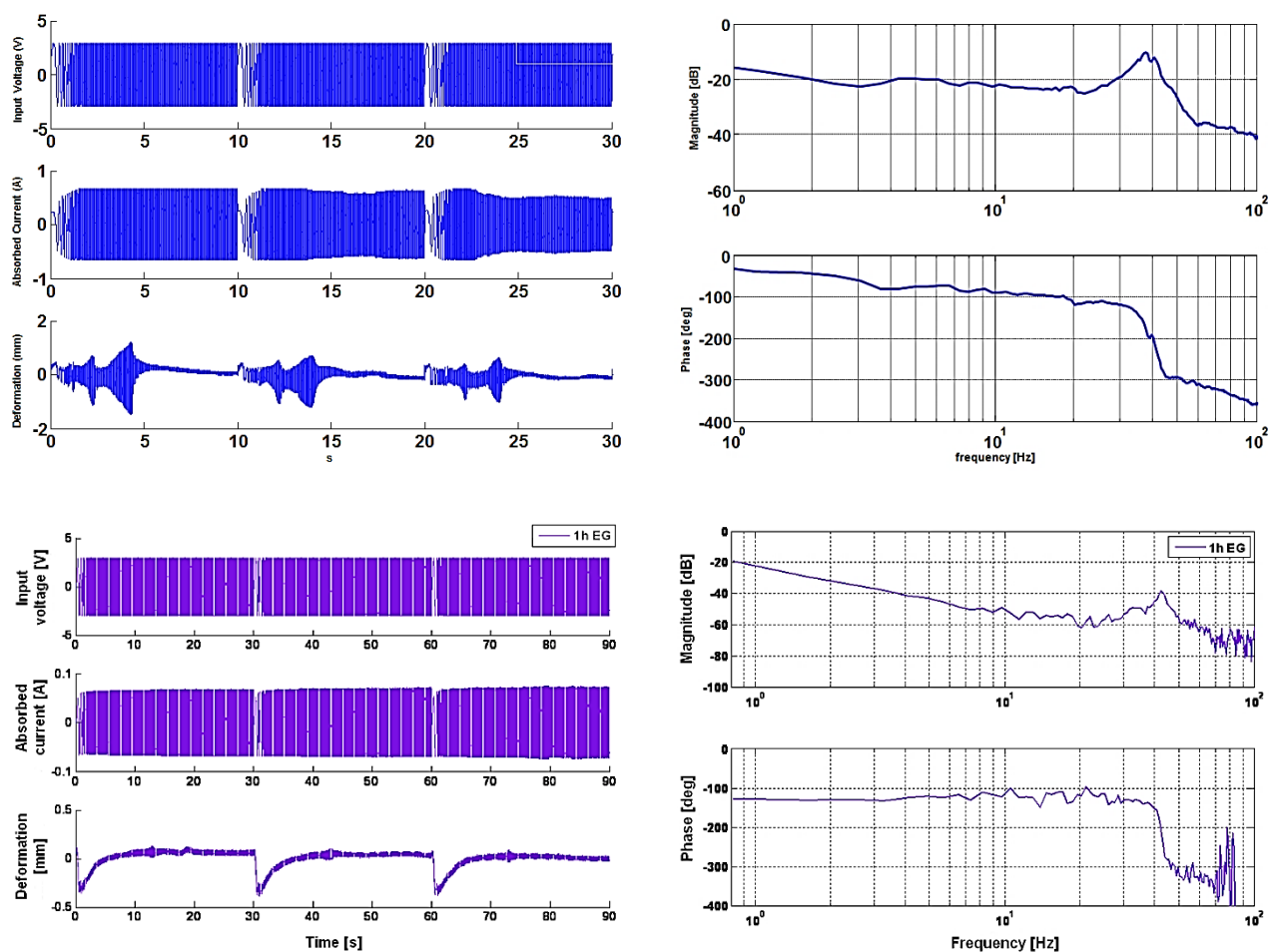
Figure 6. Actuator frequency sweep measurement (input and output signal) and Bode diagram of IP^{2}C in H_2O (blue) and EG (violet).
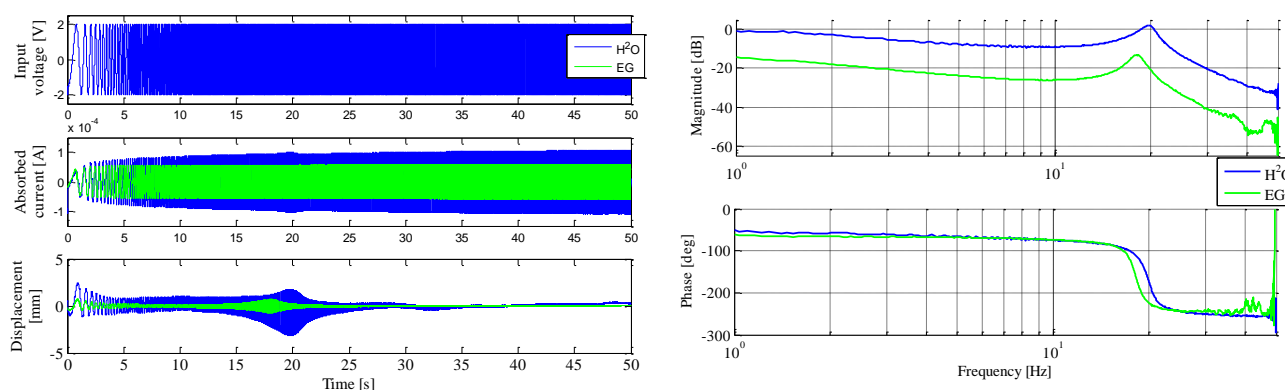

Figure 7. Actuator frequency sweep measurement (input and output signal) and Bode diagram of IPMC/H_2O (blue) and IPMC/EG (green).

When EG is used as solvent (Table 2), it is possible to observe that the absorbed current and, consequently, the deformation of devices, are lower with respect to the ones obtained using H_2O. These results can be explained taking into account several factors: EG has a viscosity higher than

water (about 16 times), higher boiling point (197.6 °C) (no evaporation during the measurements) and electrolysis phenomena are absent. Moreover, the surface resistance increases also because the electrode, after swelling with EG, could be degraded due to expansion phenomena [27]. Finally, EG containing devices show lower capacity to accumulate charges close to the electrodes (as indicated by the magnitude of the absorbed currents). This consideration is in agreement with observed deformation values that are higher for devices containing water regardless of the device type. The unusually high value of absorbed current recorded in the case of the IP^2C/H_2O sample can be attributed to the presence at membrane/conductive polymer interface of pseudocapacitive phenomena [46]. Consequently, the actuation response is lower than that with H_2O but they have higher durability. Moreover, while samples with water cannot be retested after a first measurement set, unless after soaking them again in water for rehydration, the EG containing ones do not need to be rehydrated, and thus the samples can be tested to obtain their complete characterization. Actuator frequency swept measurements and Bode diagram of the devices EG are reported in Figure 7.

4. Conclusion

In this paper, the fabrication processes, the mechanical, thermal and electromechanical behaviour of IPMCs and all organic electroactive transducers (IP^2Cs), fabricated starting from Nafion®117, have been studied and compared. Regarding the manufacturing procedures, the one required to produce IPMC is complex, long and expensive while for IP^2Cs it is easier, faster and cheap. In fact, only 1 day is required to fabricated IP^2C instead of 5 days necessary for IPMC; moreover the manufacturing cost is 0.37 €/cm^2 for IP^2C against 7.55 €/cm^2 for IPMC. Regarding the influence of the kind of electrode (Pt in IPMC and PEDOT/PSS in IP^2C), it exerts a barrier effect influencing the solvent loss in the devices during the operating times. It is possible to observe, by solvent uptake data, that in IPMC there is a higher loss of solvent due probably to the fractures present in the surfaces of Pt electrode with respect to the unbroken PEDOT/PSS film in IP^2Cs. Comparing the TGA data, the thermal properties of both the devices don't show differences up to 150 °C while, at higher temperatures, IPMC shows higher thermal stability due to the presence of platinum on the surface. DMA results show that storage modulus of IPMC is lower than the one of IP^2C. Also in this case it can be attributed to the broken and not uniform surface of Pt electrode in IPMC as shown by SEM. Relatively to the electromechanical transduction, EG based devices absorb much less current with a negative effect on the corresponding deformation. Such a clear change is not, anyway, observed in the comparison of IP^2Cs with IPMCs.

If EG is used as solvent instead of water, the solvent uptake, the thermal stability and the storage modulus decrease both in IPMC and IP^2C with respect to the ones obtained using water but, when used as actuators, the devices show higher durability, there is not necessary to rehydrate and it is possibility to reach a constant deformation.

In summary, the performances of IPMCs and IP^2Cs based on Nafion®117 are function of kind of electrode and solvent, without highlighting a significant superiority in the overall performance of one of the two technologies. Nevertheless, the lower production times and costs suggest that IP^2Cs are a possible alternative to IPMCs.

Acknowledgments

Conflict of Interest

All authors declare no conflicts of interest in this paper.

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