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Piezoresistive polymer composites based on polyether block amide and carbon nanotubes for self-sensing medical urinary catheters

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ABSTRACT

There is a large current need for new and improved approaches to treat chronic diseases such as non-neurogenic bladder diseases, the solution to prevent urethritis or inflammation of the urethral meatus being to slide a catheter along the urethra. In order to improve this procedure, it would be advantageous to place sensors in the catheter, allowing to monitor forces and deformation along the process. This work reports on a new generation of functional, sustainable piezoresistive sensors for their implementation in catheter medical devices. Composite films based on polyether block amide with varying contents of multiwalled carbon nanotubes (MWCNTs) as fillers have been produced with MWCNT contents up to 5 wt%. Further, their morphological, thermal, mechanical, electrical and piezoresistive functional response have been evaluated. Composite materials with suitable filler dispersion have been obtained, with a maximum electrical conductivity of 9×10^{-3} S.m^{-1} for the samples with the highest filler content of 5 wt% of MWCNT, the percolation threshold is between 1 and 2 wt% MWCNT content. All composites show appropriate piezoresistive behavior, with the gauge factor (GF) ranging between 0.5 and 1.5. At a maximum deformation of 5 mm, a composite with 3 wt% of MWCNT dip-coated on a catheter demonstrates an exceptional GF ~ 4.5. Additionally, an electrical system was developed to demonstrate the suitability of the self-sensing catheter for practical applications, by detecting bending deformations in real time. This work shows that these sustainable polymer-based nanocomposites can be used in the biomedical industry due to their excellent piezoresistive characteristics.

1. Introduction

Nowadays, several countries are experiencing a growing rate of aged population and an unprecedent increase in multimorbidity, which is leading to strong challenges in the healthcare services provided to populations [1,2]. Elderly care, stroke rehabilitation, chronic diseases and physiotherapeutic treatment requires a long-time commitment of medical and human resources [3,4]. In recent years and in an effort to address some of these challenges, it has been an increase effort in the development and application of digital technologies in health care services [5]. The concept of internet of things (IoT) appears in these specific topics as a new and needed trend. IoT is a system of interrelated physical objects ("things") that are embedded with sensors and software for the purpose of connecting and exchanging data with other devices and systems over the internet [6,7]. The acquisition of data is particularly important for the development of this new field, the monitorization of the heart rate for a post stroke rehabilitation with the use of wearable sensors being a perfect example of this [8,9]. Numerous applications are already being implemented in the field of health care not only in health condition monitoring, but also in rehabilitation assistance for lost limbs

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and prosthetics adaptation [10,11], as well as in the area of peripheral nerve injuries (PNIs) [12]. Having this in mind, the fabrication and optimization of sensors is of the most utterly importance and there are a large variety of different sensors that are required in this specific area of health monitorization, including pressure, force, pulse oximetry and temperature sensors, among many others.

In the specific case of personalized health monitoring, piezoresistive sensors, able to convert a mechanical stimulus to an electrical signal, are suitable for force, deformation and shape variation monitoring, both under quasi-static and dynamic conditions, being therefore demanded for a large variety of applications [13]. Piezoresistive sensors offer a series of advantages, including simple fabrication methods and working principle, low energy consumption, high sensing range for a long and stable period of time, and low cost when compared to other types of sensors [14,15]. One of the most interesting types of piezoresistive sensors, are the ones based on polymer composites, composed by a polymeric matrix and conductive fillers, the latter allowing to tune the electrical and mechanical characteristics of the polymers and, therefore, the piezoresistive functional response [16]. Different polymer matrices have been implemented for polymer based piezoresistive sensor development [16,17], the majority deriving from petroleum oil and requiring hazardous solvents during processing [18]. Thus, more sustainable approaches are needed in this area to advance in the implementation of more environmentally friendly technological approaches and solutions.

A possible way to address the latter issues is to replace synthetic polymers for natural polymers with characteristics including biocompatibility, an essential requirement in devices to be placed inside the human body [19], biodegradability [20], and, in some cases, being processable with environmental friendly solvents, including water [21].

Different natural polymers such as natural rubber [22], silk fibroin [23] and cellulose [24] have already being used as polymer matrix in piezoresistive sensors for different applications. However, this is still a very recent area of research, and more studies are required addressing the tailoring of the functional properties of the sensors, their stability over time and their implementation into proof-of-concept devices.

This work introduces a new type of piezoresistive sensors based on a sustainable polymer and varying conductive filler content in order to tune the morphology, electrical and mechanical properties and functional piezoresistive response, allowing to optimize characteristics for medical device application.

The polymer selected was a thermoplastic elastomer, polyether block amide (PEBAX), composed of blocks of hard polyamide (PA) and flexible polyether (PE) and containing 90 % renewable carbon. Thus, this biocompatible polymer allows a wide range of hardness and flexibility values, depending on its specific composition, it shows strong cold impact resistance and is shows an efficient recovery during repeated flexural cycling [25,26]. The use of this polymers has already been demonstrated in sports gear, including football shoes and sky boots [27]. PEBAX has been also introduced as a possible alternative for the production of medical catheters [28].

Composites with different filler content up to 5 wt% multiwalled carbon-nanotubes (MWCNT) content have been prepared and the electrical, mechanical and electromechanical properties evaluated. The optimized material formulations have been printed on a catheter and a proof of concept is presented to assess the viability of the developed sensors for biomedical applications.

2. Experimental

2.1. Materials

Polyether block amide (PEBAX, Rnew 72R53 SP 01) with a molecular weight Mw = 13 000–23 000 g/mol was supplied by Arkema. Multiwalled carbon nanotubes (MWCNT) with reference NC7000, an average diameter of 9.5 nm, length of 1.5 μm and carbon purity of 90 %, were purchased from Nanocyl. Formic acid 98–100 % (FA) solvent was obtained from Supelco. All materials were used as purchased.

2.2. Preparation of the composites

The composites were prepared by solvent casting (Fig. 1) with different percentages of MWCNT: 0, 1, 2, 3, 4 and 5 wt percentage (wt %). The first point was to disperse in formic acid with the help of an ultrasound bath for a period of 3 h at a temperature between 25 and 30 ºC the corresponding MWCNT content allowing them a suitable dispersion. After this, the developed polymer was added with its corresponding solvent 1 g/6 ml. After that, the solution was magnetically stirred at 80 ºC until the polymer was fully dissolved.

The solutions were then poured in a glass substrate and, with the help of an extensor with 700 μm space, the solution was spread to obtain uniform films by doctor blade (Fig. 1). The films were placed in a conventional oven (PSelecta, model no 2000208) at 120 ºC for 10 min so that the solvent evaporates. The composites thickness ranged between 15 μm and 70 μm, depending on the specific filler content.

In the succeeding, the composites will be recognized as yMWCNT/PEBAX, y identifying the filler content in the composite.

2.3. Samples characterization

Morphological characterization of the samples was executed by scanning electron microscopy (SEM) with a Hitachi S-4800 equipment, allowing also to determine the dispersion of the MWCNT within the polymer matrix. Surface and cross-section images were obtained at a magnification of 5 000 × .

Fourier transformed infrared spectroscopy analysis was carried out in a Jasco FT/IR-4100 equipment in the attenuated total reflectance (ATR) mode at room temperature. FTIR spectra were collected from 600 to 4000 cm^{-1}, at scans with resolution of 4 cm^{-1}.

X-Ray Diffraction (XRD) was applied to study the structure of the composites. A Philips X´Pert, Pro diffractometer was used, along with Cu Kα radiation, 40 kV of applied voltage, and 40 mA of current.

Raman spectra were recorded with a confocal Raman microscope (Renishaw, InVia, UK) at ambient temperature with excitation wavelength of 532 nm.

Thermal properties were evaluated with the help of Differential Scanning Calorimetry (DSC) from 0 to 200 ºC at a rate of 10 ºC/min in a dry nitrogen atmosphere using a Mettler Toledo 822e set up. TGA was conducted using a TA instruments Q50 analyzer with a heating rate of 10 ºC/min under a nitrogen atmosphere.

Mechanical tests were carried out in a Shimadzu model AG-IS with a 500 N load cell in the tensile mode. To prepare the samples they were design in rectangular shapes with dimensions 5 × 10 mm and with thickness from 15 to 70 μm and analyzed at deformation rates of 5 mm/min. The initial modulus was evaluated from the stress-strain measurements up to 5 % of strain, measured for 3 different samples for every material.

The electrical resistance (R) in volume mode was obtained after measuring the current-voltage (I-V) response by applying voltage (V) steps of 1 V from −10 to + 10 V and measuring the electrical current (i) with an automated picoammeter/voltage source Keithley 6487. 5 mm diameter Au parallel contacts were previously deposited on both sides of the samples with a Polaron SC502 sputter coater. The electrical resistivity (ρ) and conductivity (σ) were calculated using the Eq. 1:

$$\rho = \frac{1}{\sigma} = R\frac{d}{A} \quad (1)$$

where, A is the area of the electrodes and d is the sample thickness.

Piezoresistive measurements were also made in the 4-point bending mode as represented in Fig. 2. The composites were glued to a polypropylene polymer flexible substrate with a thickness of 0.5 mm. The electrodes on the composite were printed with a silver ink (Agar

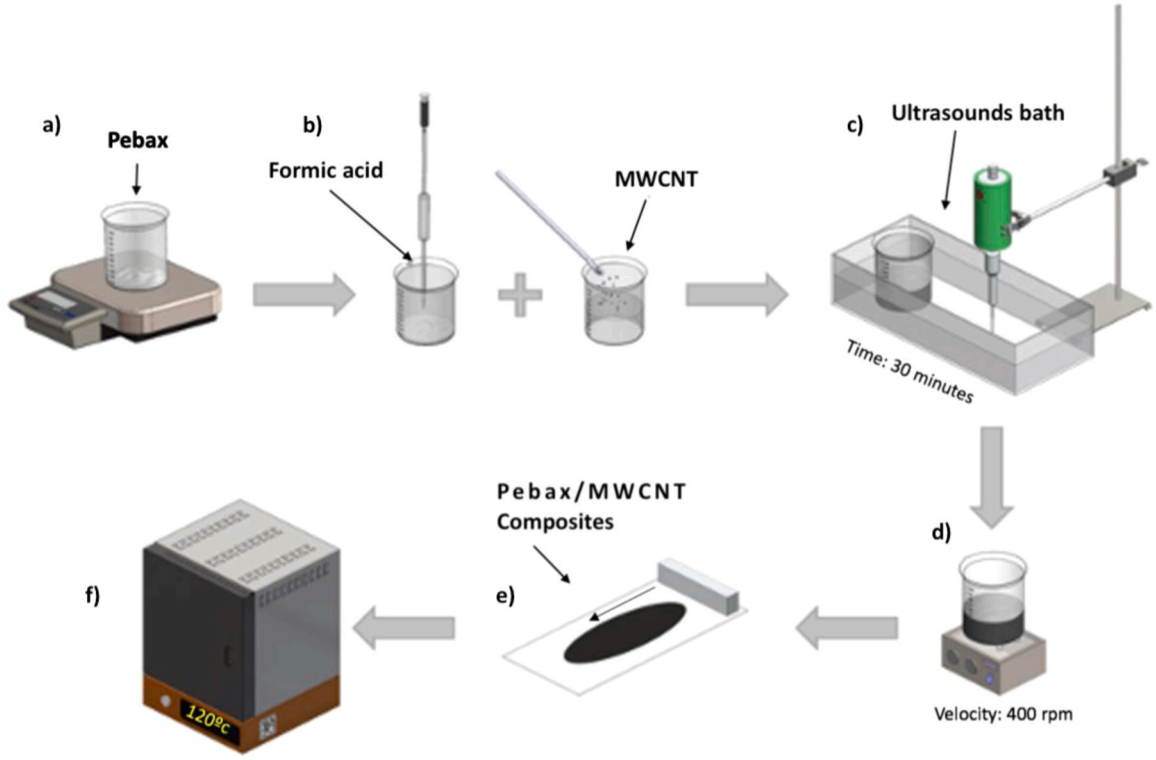


Fig. 1. Schematic representation of the procedure to develop the MWCNT/PEBAX nanocomposites: a) weight of the polymer, b) addition of the solvent and the filler c) dispersion of the filler content d) mixing the solution with a constant speed, e) doctor blade procedure, f) evaporation of the solvent.

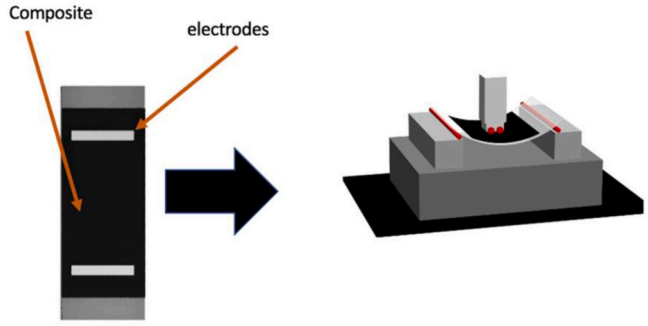


Fig. 2. Schematic representation of the piezoresistive performance test in 4-point bending tests.

scientific) with an area of 25 mm × 11 mm of (length x width). The electromechanical response was evaluated for the 1MWCNT/PEBAX, 3MWCNT/PEBAX and 5MWCNT/PEBAX samples from 0.5 to 5 mm of bending at different deformation speeds (1–5 mm/min).

The piezoresistive sensibility of the composites was evaluated using the equation:

$$GF = \frac{\Delta R/R}{\varepsilon} \tag{2}$$

where ΔR is the variation of resistance, R is the initial resistance and ε is the applied deformation, that can be obtained using the theory of pure bending [29] that can be translated in the equation:

$$\varepsilon = \frac{3dz}{5a^2} \tag{3}$$

where d is the thickness of the support and the sample, $d = 0.759$ mm for 1MWCNT/PEBAX; $d = 1.18$ for 3MWCNT/PEBAX and $d = 0760$ mm for 5MWCNT/PEBAX sample, z is the vertical displacement, up to 5 mm, and a is the distance between electrodes 25 mm.

2.4. Self-sensing catheter implementation: prototype development

To evaluate the performance of the piezoresistive composites, a functional self-sensing biomedical device based on a child urinary catheter- a flexible tube that is used to empty the bladder and collect urine in a drainage bag- has been developed based on the developed materials, allowing to monitor the deformation, mimicking a real application. A commercial catheter (LoFric origo REF 44210) was used and the natural polymer PEBAX based inks reinforced with 3 wt% MWCNT was implemented as piezoresistive sensors to determine the bending movements. Fig. 3 shows the process used to place the 3MWCNT/PEBAX piezoresistive inks on the catheter.

For the dip coating procedure, the catheter was embedded in a goblet with the prepared ink solution (Fig. 3b). The deposited ink was then cured at 25 °C for 10 min (PSelecta, 2000208) to remove the solvent. The temperature used in this step was different form the one previously used in the composites due to the properties of the material present in the urinary catheter (polyolefin-based thermoplastic elastomer). For high temperatures, the flexibility of the urinary catheter will be compromised.

Further, for signal acquisition, two silver electrodes were deposited at a distance of 30 mm within the piezoresistive layer using a brush, and conductive electric paint (Bare conductive with a sheet resistance of 55 Ω/sq at 50-micron film thickness) was used to connect a copper wire to each silver electrode. The copper wires were connected to a Wheatstone bridge in the position of the resistance *Rs* (Fig. 4).

The same value of 170 kΩ was assigned to the remaining bridge resistances (the R0 of the sensor). The bridge output was directly connected to a 5 V-referenced 24-bit analog-to-digital converter (ADC). The ADC was controlled by a microcontroller Arduino Uno that receives the data from the ADC via Serial Peripheral Interface (SPI) and sends the raw data to a graphical interface on a computer for analysis.

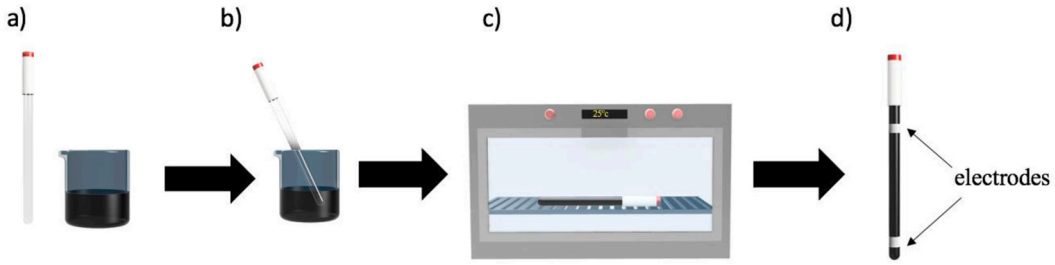


Fig. 3. Schematic representation of the implementation of piezoresistive ink on the catheter a) the catheter and the ink were prepared, b) the ink was placed in the catheter by dip-coating, c) cured and d) silver ink was deposited on the catheter to serve as electrodes.

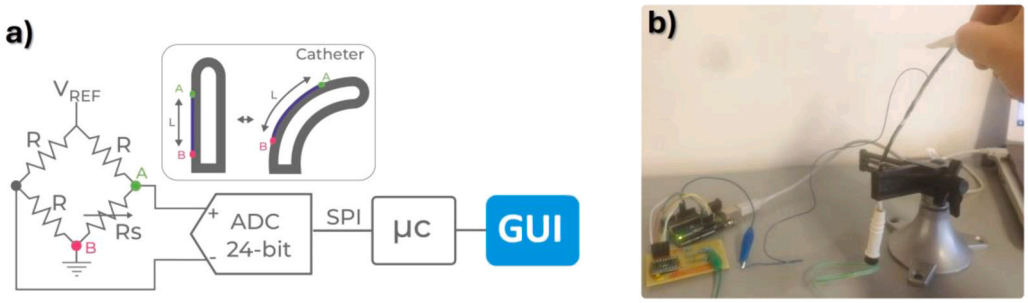


Fig. 4. A) Electronic circuit acquisition and b) corresponding image of the prototype.

Based on the piezoresistive effect of the material, the results provided proof of concept for a responsive catheter. By manually bending the catheter tip with a non-conductive tweezers, various bending deformations were applied. Based on the amount of catheter deformation, it is possible to detect multiple positions (see video in supplementary information). The material resistance increases proportionally to bending deformation, in a reversible way, returning to the original resistance values when the deformation is released.

3. Results and discussion

3.1. Morphological features, vibrational spectra and thermal characterization

SEM images were used to evaluate the composites' morphology, as presented in Fig. 5. Fig. 5 shows representative cross-sectional SEM images of the different samples, allowing also to assess the dispersion of MWCNTs in the PEBAX polymer matrix. The morphology of the samples remains unaffected by the addition of the carbon nanotubes, and a compact microstructure free of voids is observed in all samples.

Fig. 5f (insert) demonstrates the good compatibilization between MWCNTs and polymer matrix, the MWCNTs being evenly distributed throughout the matrix for all samples without large aggregates. Thus, the PEBAX polymer composites exhibit a compact morphology suitable for piezoresistive sensor applications.

After mechanical stretching within in the plastic region (up to 8 % strain), just the appearance of small cracks is observed in the samples, as shown in the SEM images in Figure S1, supplementary information.

Fig. 6a) shows the vibrational modes of the samples obtained by FTIR-ATR measurements. The obtained spectra of the PEBAX polymer sows the vibrational modes of the PA and PE blocks that constitute it. Further, it is observed that the MWCNTs content does not affect the vibration modes of the PEBAX. In all samples, the main vibration peaks of the PA block are detected at 3292, 1640 and 1539 cm^{-1}, which correspond to the –NH– stretching of the amide group, amide I band and amide II band, respectively [30].

For the PE block, the main vibration bands at 1733, 1277 and 1112 cm^{-1} are detected, corresponding to the C═O stretching of ester group, C–O–C asymmetric stretching and C–O–C symmetric stretching, respectively [30].

Fig. 6b) shows the X-ray diffractograms of neat PEBAX and composites, showing crystalline peaks at 19.8º and 23º, corresponding to the (002) (α2) crystal type and γ-crystalline phase of the PA chain segment, respectively [31]. These peaks are observed in all samples, demonstrating the semicrystallinity of the composites and that the MWCNT content does not affect the crystalline phase.

Figure S2 shows the Raman spectra of the PEBAX composites, being characterized by the bands at 1347 and 1443 cm^{-1}, attributable to the second -order Raman modes of D-band [32], regardless of the MWCNT content.

The DSC curves and TGA thermograms are presented in Fig. 6c and d for neat PEBAX and the corresponding composites. For all samples, Fig. 6c shows an endothermic peak at 183–185 ºC that corresponds to the melting of the PA crystalline phase [30]. Furthermore, it is observed that the MWCNT content does not affect the melting behavior of the PA block. For the 1MWCNT/PEBAX and 4MWCNT/PEBAX samples the melting behavior is made up of two peaks (Fig. 6c), which can be attributed to two distinct crystalline conformations of PA [33].

Given that the PEBAX polymer contains a significant amount of PA, Fig. 6d) shows the TGA thermograms of the samples, showing a single-step degradation at a temperature of about 415–450 ºC. This temperature corresponds to the degradation of the PA and PE blocks [34,35]. The MWCNT content of the composites has no effect on this degradation.

Therefore, the inclusion of the MWCNT in this polymer matrix has no effect on the crystalline properties, vibration bands, or thermal behavior.

3.2. Mechanical and electrical characterization

The mechanical behavior of the composites based on PEBAX with 0–5 wt% MWCNT content is shown in Fig. 7a), while the calculated values of the Young's modulus in the elastic region, obtained by the secant method at 2 % deformation, are illustrated in Fig. 7b). It is observed that the mechanical behavior is typical for a thermoplastic polymer and that the addition of MWCNT affects the maximum strain and stress, as well as the Young modulus. The mechanical behavior of

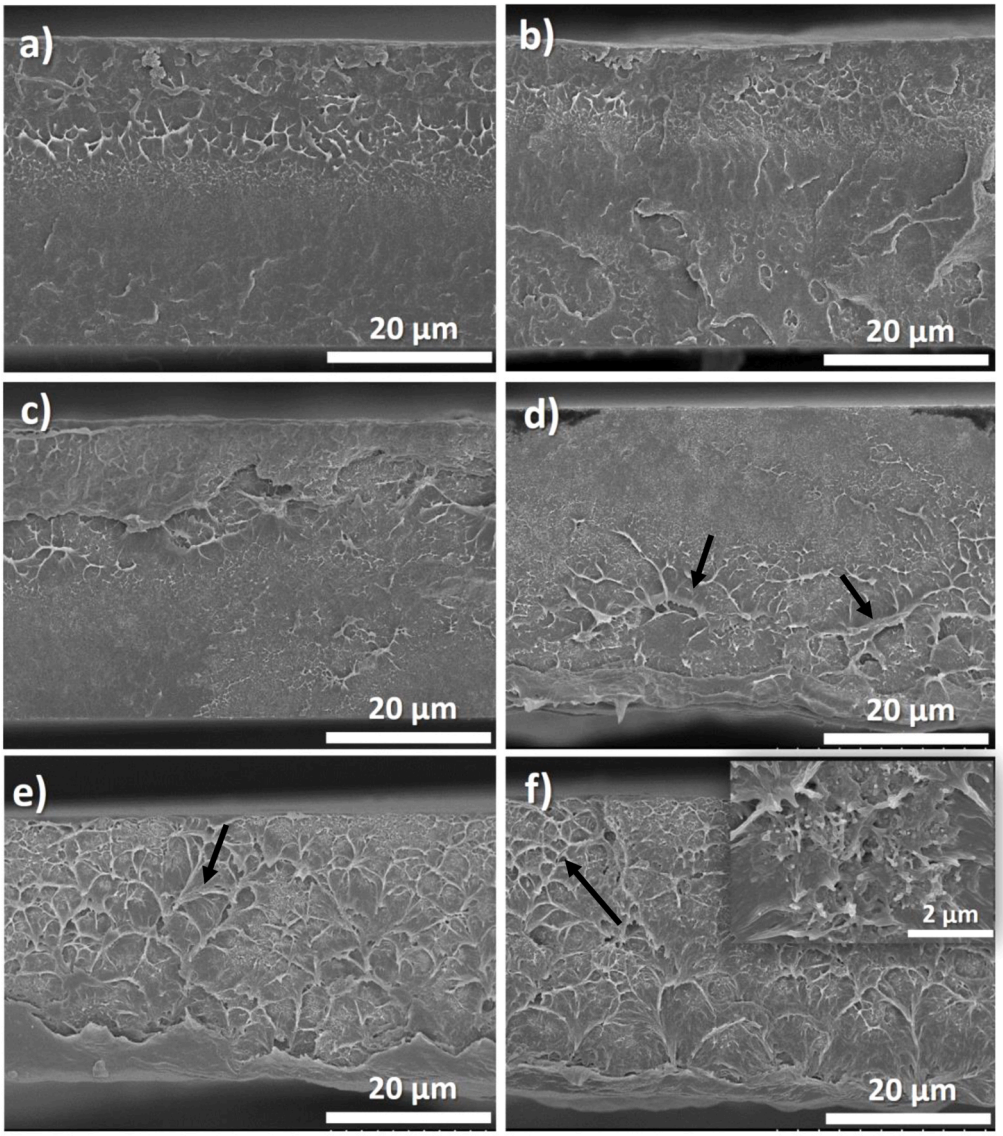


Fig. 5. SEM images of the cross-section of a) 0MWCNT/PEBAX, b) 1MWCNT/PEBAX, c) 2MWCNT/PEBAX, d) 3MWCNT/PEBAX, e) 4MWCNT/PEBAX and f) 5MWCNT/PEBAX (insert: higher magnification). the arrows identify the MWCNT in certain small aggregates.

PEBAX is strongly dependent on the PA block [30], which is achieved by the chemical crosslink. The hydrogen bonding and the softs segments of polyether provides flexibility to the material [36].

The Young's modulus (Fig. 7b) is nearly independent of the MWCNTs added to a polymer matrix. Also, these composites show high Young's modulus above 0.4 GPa, the hard PA crystalline domains being responsible for the stiffness of the material. Yield stress and strain are influenced by the MWCNT content, indicating the effectiveness of MWCNT strengthening, due to the good dispersion in the polymer matrix [36]. As a conclusion, the composites show suitable mechanical properties for functional applications.

The I-V curves of the polymer matrix and composites are linear (ohmic) for all samples (Fig. 7c). Due to the conductivity of the MWCNT [37], Fig. 7c shows that the addition of MWCNT in the polymer matrix increases the slope of the IV curves. Eq. 1 was used to calculate the electrical conductivity (σ), and Fig. 7d shows the value of σ as a function of the MWCNT content. With the exception of 4 wt% of MWCNT, it is noticed that the electrical conductivity value (σ) increases as the MWCNT content increases. For the neat polymer matrix, the σ value is 2.04×10^{-8} S.m^{-1}, but when the MWCNT is increased to 5 wt%, a maximum σ value of 9.0×10^{-3} S.m^{-1} is obtained, the composites becoming electrically conductive. The percolation threshold for the composite is between 1 and 2 wt% of MWCNT which depends on the formed MWCNT network [38].

Based on mechanical and electrical results, these composites have excellent potential for piezoresistive sensor applications.

3.3. *Piezoresistive response*

For piezoresistive sensors, the composites are mechanically requested, and the resistance variation evaluated. The piezoresistive behavior depends on the percolation threshold to obtain high sensitivity [39], where composites with higher filler contents typically need large deformations to obtain stable piezoresistive responses [40]. The piezoresistive response was evaluated under different bending mechanical solicitations (1–5 % maximum strain) and different deformation speeds.

Fig. 8a) shows the piezoresistive response for the composites for 10 loading-unloading bending cycles at 5 % maximum uniaxial strain and deformation speed of 5 mm/min. For other applied strains, the behavior is similar. Fig. 8b) shows the gauge factor (GF) as a function of applied bending. For all composites, it is observed an excellent response due to the mechanical and electrical characteristics of the PEBAX composites.

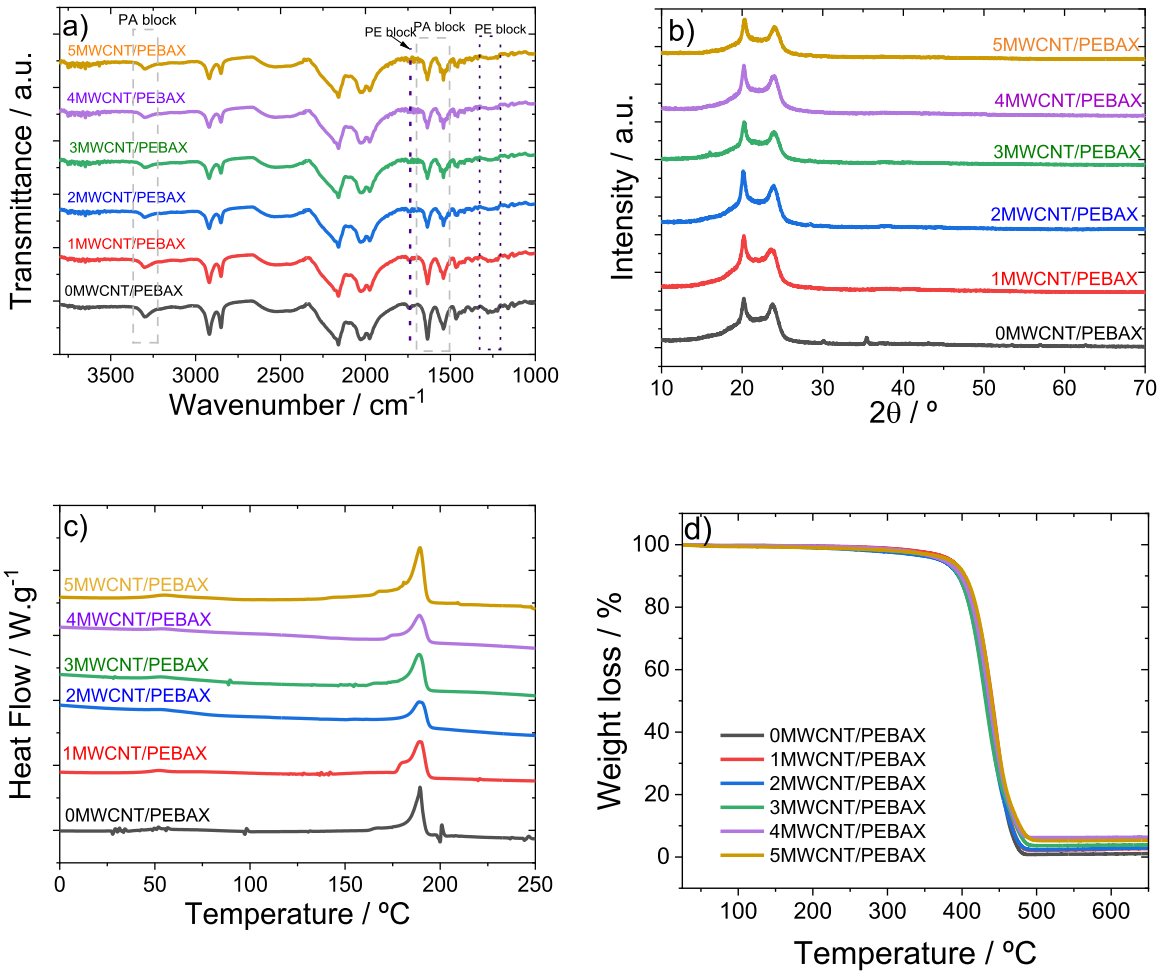


Fig. 6. A) FTIR spectra, b) X-ray difraction, c) DSC curves and d) TGA thermograms of the composites based on PEBAX polymer with 0–5 wt% MWCNT content.

Fig. 8a) shows the good linearity between relative electrical variation and applied bending for all composites. It is noted that the 1MWCNT/PEBAX and 5MWCNT/PEBAX composites do not fully recover from deformation release because to long-term alterations and slow relaxation of the conductive network.

The piezoresistive sensitivity under bending solicitation ranges from 0.5 to 1.5 for all composites (Fig. 8b). Despite an increase the filler content, the 1MWCNT/PEBAX and 3MWCNT/PEBAX samples show similar GF values between 0.5 and 0.7 for deformations between 1 and 5 mm as presented in Fig. 8b). It is to notice that both composites present a GF dominated by the geometrical contributions ($1+2\nu$). However, in the 5MWCNT/PEBAX sample the values are much higher showing the prevalence of the intrinsic resistivity changes. For 5MWCNT/PEBAX, it is found that the intrinsic resistivity changes as the bending deformation increases, causing the GF to decrease. This behavior is not observed for other composites and is related to the reconfiguration/relaxation of the MWCNT network [41].

Despite the resistance value decrease in each cycle this has no particular adverse effect in the overall use of the sensors, the GF is constant in each cycle and this variation can be corrected when the signal acquisition board developed to collect the data.

This GF observed for this polymer matrix is also similar to that observed for other sustainable polymer matrices such as silk fibroin or carboxymethyl cellulose, among other polymers [38,42–44].

Based on its renewable nature and piezoresistive behavior, the composite material offers a suitable strategy for biomedical applications that takes into account the needed sustainability of technological solutions [45,46].

3.4. Design of a self- sensing medical device

Despite the 3MWCNT/PEBAX composite is not the sample with the best GF values in comparison with the other ones, is shows an improved stability over repeated cycling (Fig. 8a). Thus, this sample was selected to develop the proof of concept. Further, as the biomedical device final objective is the introduction in the interior of the organism, the least filler content in the application the better in terms of safety. As more MWCNT content is in the sample more defects in the matrix will surge causing the composite to fracture under less stress reducing the overall flexibility of the developed sensors[36].

By using a dip coating method, the 3MWCNT/PEBAX composite was incorporated into the catheter to assess the functional performance of the piezoresistive composites in catheter applications (Fig. 9).

The piezoresistive response of the sensor on a commercial Foley urine catheter under for lateral bending deformations of 5 mm of the tip for over 40 cycles is shown in Fig. 9a.

Excellent linearity between the mechanical and electrical response under mechanical bending is observed in Fig. 9a, where the catheter's resistance changed linearly in response to the bending stimulus. The piezoresistive sensitivity of the 3MWCNT/PEBAX composites is 4.5, where this value is higher than that observed in Fig. 9b) due to the excellent compatibility between the ink and the catheter surface and the load/deformation transfer to the sensor.

Furthermore, as shown in Fig. 9b, this catheter with a piezoresistive sensor was connected to an electronic system to evaluate the resistance variation in real time during different (in direction and intensity) bending solicitation. The electrical resistance variation in response to

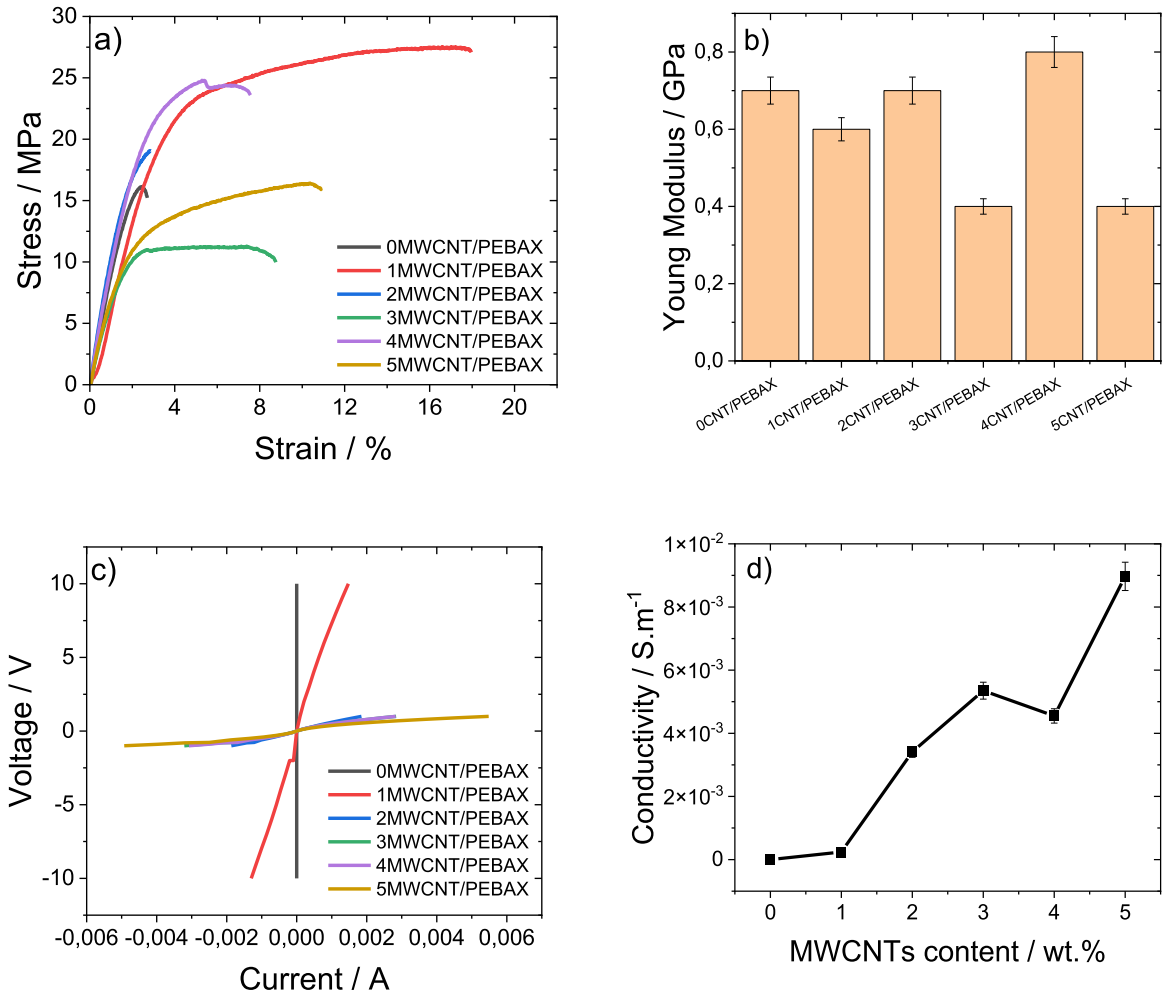


Fig. 7. A) Stress-strain and c) I-V curves of the composites based on PEBAX polymer with 0–5 wt% MWCNT content. B) young modulus and d) electrical conductivity values as a function of the MWCNT content.

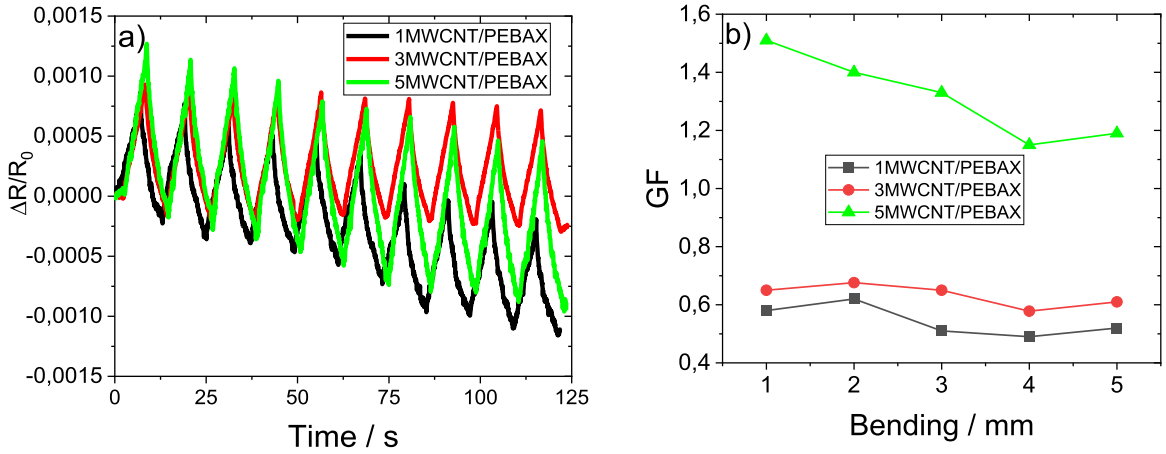


Fig. 8. A) Piezoresistive bending behavior for 10 bending loading-unloading cycles at v= 5 mm/min for the PEBAX composites with 1, 3 and 5 wt% MWCNTs and b) gauge factor value for the composites from 1–5 mm of maximum bending deformation.

the different bending modes on the catheter are depicted in Fig. 9b), the resistance of the sample in the relaxed state being identified as (1) and in the bent state as (2).

Also, the catheter presents excellent response under different deformations as shown in Fig. 9b. A hybrid polymer-based polyimide/SU-8 catheter tip MEMS gauge pressure sensor has been reported in the literature with good sensitivity [47], where based on the behavior observed in Fig. 9, the printed PEBAX allows for the real-time measurement of a commercial catheter's bending movements, which presents a viable way for the biomedical industry to provide patients with improved, more precise and less intrusive care.

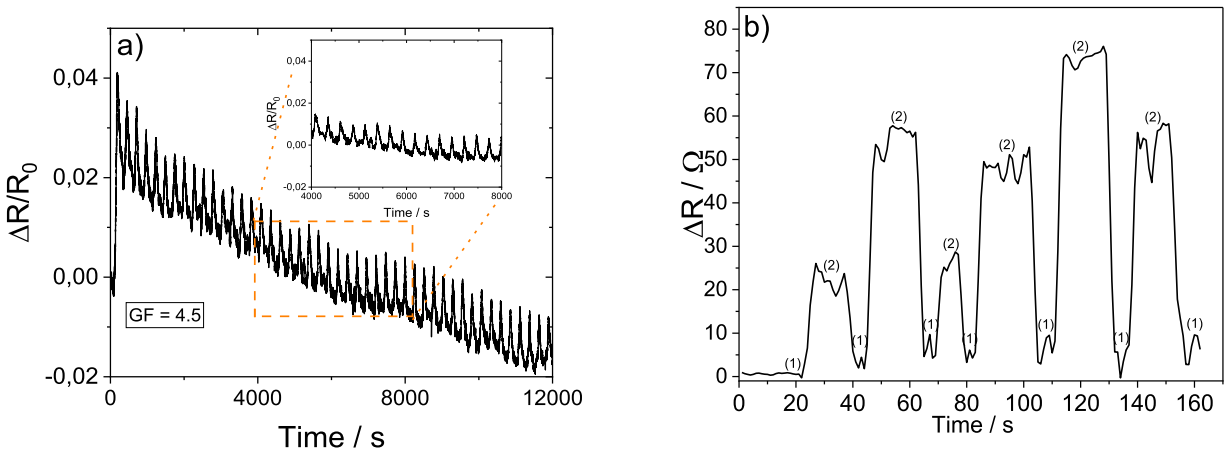


Fig. 9. A) Piezoresistive response of 3MWCNT/PEBAX applied to the catheter and b) resistance variation of the catheter with the composite coating applied by dip-coating connected to the electronic circuit.

4. Conclusions

Polyether amide block (PEBAX) is an interesting thermoplastic elastomer for the development of multifunctional composites, as it contains 90 % renewable carbon and can be processed using additive manufacturing. PEBAX composites with conductive multiwall carbon nanotubes (MWCNTs) were processed by solvent casting technique with different contents of MWCNTs (0, 1, 2, 3, 4 and 5 wt%) for application in medical catheters. Furthermore, the composite with adequate electromechanical performance was incorporated into the catheter surface by dip-coating technique to monitor its deformation in real time.

For these developed composites, the morphology, thermal, mechanical and electromechanical properties in stretching and bending mode are evaluated.

The composites reveal a homogeneous dispersion of MWCNT and the addition of MWCNT does not affect the vibration bands and thermal properties of the polymer.

The content of MWCNTs in the polymer matrix affects the mechanical and electrical properties. The Young's modulus varies from 0.7 GPa for the PEBAX matrix to 0.8 GPa for the sample composed with 4 wt% MWCNTs. Further, the electrical conductivity ranges between 2.04×10^{-8} S.m^{-1} for the pure polymer matrix and 9×10^{-3} S.m^{-1} for the 5 wt% MWCNT content composites. The percolation threshold is between 1 and 2 wt% MWCNT content. These composites exhibit suitable piezoresistive behavior with the GF varying between 0.5 and 1.5 under bending deformation.

The 3MWCNT/PEBAX composite was dip-coated on a catheter to obtain a self-sensing catheter with a GF $\sim$ 4.5, allowing to detect bending deformations in real time.

This work shows that it is possible to obtain sustainable polymer-based nanocomposites with excellent piezoresistive properties suitable for implementation in the biomedical area.

CRediT authorship contribution statement

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jallcom.2025.181447.

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