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Development of polymer wicks for the fabrication of bio-medical sensors

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ABSTRACT

Polymer based wicking structures were fabricated by sintering powders of polycarbonate (PC), ultra-high molecular weight polyethylene and polyamide 12, aiming at selecting a suitable material for an innovative electroencephalography (EEG) bio-electrode. Preliminary experiments showed that PC based wicks displayed the best mechanical properties, therefore more detailed studies were carried out with PC to evaluate the influence of powder granulometry and processing parameters (pressure, temperature and time) on the mechanical properties, porosity, mean pore radius and permeability of the wicks. It was concluded that the mechanical properties are significantly enhanced by increasing the processing time and pressure, although at the expense of a significant decrease of porosity and mean pore diameter (and thus permeability), particularly for the highest applied pressures (74 kPa). However, a good compromise between porosity/permeability and mechanical properties could be obtained by sintering PC powders of particle sizes below 500 μm at 165 °C for 5 min, upon an applied pressure of 56 kPa. Moreover, PC proved to be chemically stable in contact with an EEG common used disinfectant. Thus, wicking structures with appropriate properties for the fabrication of reusable bio-electrodes could be fabricated from the sintering of PC powders.

1. Introduction

Electroencephalography (EEG) is the recording of the brain electrical activity along the scalp [1]. EEG is nowadays the most widely used brain imaging technique. The main areas of EEG application are: (i) sleep monitoring, (ii) clinical diagnosis and (iii) long-term epilepsy monitoring. Currently used electrodes are metallic (silver is the most common metal) and require application of a conductive paste or gel to decrease the skin/electrode impedance and facilitate signal transfer. Their application is thus time-consuming and error-prone. Furthermore, extensive cleaning of skin, hair and equipment is required after the exam. Their counterparts, the so-called dry electrodes, eliminate the need to use gels or pastes but display high skin-electrode impedances, and exhibit high sensitivity to movement artefacts [2–4].

This work aims at developing the material for a conceptually different EEG electrode that will combine the advantages of the “wet” and “dry” sensor systems, while addressing most of their drawbacks. A specifically developed polymer wick will be the core electrode material. Like in a felt-pen, the upper part of the electrode body will work as a moistener reservoir, for electrode autonomy, and the tip will establish the skin contact. Hence, a reliable low impedance electrode–skin contact will be achieved without the use of gel paste, by the continuous delivery of a small amount of a moistener solution at the electrode/skin contact point. The moistener will be promptly absorbed by skin without spreading, dirtying or damaging the hair.

Wicks are porous structures commonly used to absorb and transport liquids mainly by the action of capillary pressure [5–7]. A good wick material exhibits a high permeability/liquid absorption capacity and can induce significant capillary liquid pressure gradients. However, these two properties oppose to each other: large pores are required for high permeability/liquid absorption, while small pores are needed to induce large capillary pressures; therefore a compromise has to be found to achieve an optimal behaviour. Experience shows that, with an appropriate liquid, reasonable permeability values and capillary action can be obtained with porosities of 50–60% and mean pore radius of 5–50 μm [7,8].

Porous interconnected polymeric structures have been used in a broad range of applications, from the biomedical area (drug controlled release, scaffolds and support for bimolecular immobilization) to filtration membranes, heat pipes and vapour chambers, sorbents, silencers, fragrance diffusers for perfumes and air fresheners and many other applications [5,6]. However, each application has its own specificities, which may require different fabrication methods. Additive Manufacturing (AM) is a family of recent fabrication techniques that can rapidly produce highly complex three-dimensional physical objects using data generated by CAD systems [9]. These techniques include three-

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dimensional printing (3D-P), fused deposition modelling (FDM) and selective laser sintering method (SLS) techniques [10–12]. The main advantages of these methods are the high porosity that can be achieved (up to 80%) and the ability to produce materials with controlled pore interconnectivity and pore sizes ranging from 40 to 1000 μm, depending on the particular technique. The SLS and 3D-P techniques originate large pore size distributions [9]. AM methods are in general expensive and time consuming, thus not suitable for mass production. The rotational moulding is an inexpensive technique but it is only applicable to a narrow range of materials and the final structure shows a high degree of closed pores [13]. The melt moulding process is often used in the microfluidics area and has the advantage of producing structures with independent control of porosity and pore size. Nevertheless, it needs high processing temperatures and residual porogen contamination may occur [14].

On the other hand, chemical methods allow obtaining polymer porous structures with controlled pore size ranging from a few nm to 100 μm, depending on the specific technique and polymer [5]. However, these techniques involve the presence of porogens and other chemicals that must be removed at the end, what has to be carefully addressed for biomedical oriented applications. The same applies to the freeze drying technique, which involves freezing a liquid suspension, followed by the sublimation of the solvent. Highly porous (up to 90% porosity) and interconnected structures are achieved in this case, with pores sizes ranging from tens to a few hundred μm [15].

Finally, the powder sintering technique is a simple and cost-effective technique and it allows the production of interconnected porous structures in a wide range of pore sizes (1–1000 μm) and porosity (up to 70%), while also offering the possibility of being applied to a large number of polymers. Furthermore it doesn't involve the presence of chemicals. For these reasons it is often preferred for the mass production of wick materials, even in the biomedical area. During this process the powder is compressed and heated at temperatures close to the melting point. The polymer particles will fuse together at their contact surfaces under the effects of applied pressure and temperature, and inter-particle mass-diffusion will occur leading to a solidified body with a complex porous structure and adequate mechanical strength [16–19]. The sintering technique will be used to fabricate the wick electrode porous structures in this work.

2. Requirements for a porous wick structure to be used as a biopotential electrode

A biopotential electrode based in a polymer wick should stock inside its porous structure a hydrating fluid to be dispensed upon skin contact, so to keep the electrode/skin contact point hydrated for the duration of the exam (some signal acquisitions may last for several hours). Therefore, porosity should be high, but the pore size should be small enough to ensure that the liquid is retained inside the structure. Liquid retention capability also depends on the properties of the hydrating fluid to be used (density and viscosity). Furthermore, the amount of hydrating fluid necessary to decrease the skin impedance is dependent on the person and even environmental conditions. Taking into consideration these variables, the porous structures to be developed should be obtained in a wide range of permeability and porosity values, so the most suitable electrode properties can be adapted in a later stage.

Regarding the required mechanical properties, the force exerted on the electrode is about 3 N, as measured by the authors in a previous work using a Nihon Kohden EEG cap system [3]. If the electrode is of the multipin type, with 24 pins and a 1 mm pin top diameter [20], each pin should be able to safely withstand a pressure of at least 1 MPa. This value corresponds to the situation where the total force is concentrated on just 25% of the pins, which is considered the worst case scenario. Furthermore, owing to the small pin diameter, the polymer particle size should have a diameter below the 1 mm limit so the structural integrity of the pin does not have to rely on a few inter-particle bonds.

3. Experimental details

3.1. Materials

Three different thermoplastic polymers were pre-tested, namely: polycarbonate (PC LEXAN 141R 111, Ge Plastic, MFI = 12 g/10 min at 300 °C), ultra-high molecular weight polyethylene (UHMWPE GUR 5113, Ticoma, MFI = 4 g/10 min at 190 °C) and polyamide 12 (PA 12 Rilsan AMNO TLD, Arkema, MFI = 69.4 g/10 min at 235 °C). All polymers were acquired in the form of pellets.

3.2. Wick production system

The wick structures were produced using a custom built sintering system. The system produces wicks with 10 mm in diameter and a length ranging between 13 and 23 mm, depending on the applied compression load. It consists of four main components, as illustrated in Fig. 1: the heating resistance which involves the whole cylinder (a), the piston (b), the support for the material (d) and the core cylinder (f). Part (c) ensures that the material is processed in the middle of cylinder (d), part (e) keeps (c) inside the cylinder (d) and (g) orifice to house the thermocouple, Fig. 1 (ii).

The heating resistance (a) is responsible for controlling the system temperature; the core cylinder (f) surrounds all components and distributes the heat generated by the resistance to the material support; the piston (b) is responsible for the raw material compaction and the material support (d) holds the material inside the cylinder during the sintering stage.

The production process starts by heating the system to the predefined processing temperature. After achieving steady state conditions, 1 g of grinded polymer is introduced inside cylinder (d). Then the sample is compressed through the action of the piston, the compression pressure being adjusted by the use of different weights placed on the material support base (b). Once the sintering process is finished, the inner subsystem (Fig. 1 — “b” to “e”) is removed and cooled, by immersion in water at room temperature. Finally the wick is collected from the support. Different wicking properties can be achieved by controlling the processing temperature, pressure and time.

Before being processed the polymer pellets are ground to a powder state in a mill in contact with liquid nitrogen. Thereafter, the powders are sieved in order to obtain fractions with different grain sizes, see Table 1.

For the preliminary sintering experiments, aiming at selecting the most suitable polymer, the grain size was set below 500 μm and all materials were processed for 5 min with a pressure of 18.5 kPa and a temperature of 165 °C, 125 °C and 160 °C for PC, UHMWPE and PA respectively (REF conditions in Table 1). Further processing was carried out with the selected polymer, PC, according with the conditions reported in Table 1.

3.3. Characterization of the wick structures

3.3.1. Chemical compatibility with the disinfectant

Polymer films with a thickness of 0.1 mm were fabricated using a hydraulic press (Manual Hydraulic Press, Specac, UK) by applying a 15,000 kg of compression force for 4 min. The processing temperature was set at 250 °C for PA and PC and 270 °C for UHMWPE. Afterwards, the materials were immersed in a 7.9 g/l solution of Control III disinfectant (Maril products Inc.) for 3 h. Control III is a commercial disinfectant used for EEG biomedical electrodes. A 10 min immersion is recommended for full disinfection. After immersion the film samples were analysed using a Fourier Transform Infrared Spectrometer (FT/IR — 4100, Jasco) in transmission mode with a 0.4 cm^{-1} resolution.