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Technical note

Laser fabrication of electrical feedthroughs in polymer encapsulations for active implantable medical devices

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ABSTRACT

Hermetic electrical feedthroughs are essential for safe and functional active implantable biomedical devices and for a wide range of other applications such as batteries, supercapacitors, OLEDs and solar cells. Ceramics and metals have previously been the materials of choice for encapsulations, while polymers have advantages of ease of mass production and end user compatibility. We demonstrate a laser sealing technology that gives hermetic, mechanically strong feedthroughs with low electrical resistance in a polyetheretherketone (PEEK) encapsulation. The conductive pathways are wires and sputtered thin films. The water vapor transmission rate through the fabricated encapsulations is comparable to that of PEEK itself.

1. Introduction

Active implantable medical devices such as cochlear replacements and retinal replacements contain electronic components that must remain fully functional under physiological conditions for long periods. The materials used for the encapsulation of these devices must be non-toxic and biocompatible. The encapsulation of the electronics has to accommodate a large number of electrical feedthroughs for receiving input signals from the body without compromising the hermetic seal [1,2,3]. The encapsulation not only protects the electronics from corrosion that would otherwise take place in the physiological environment, but protects the body from the release of toxic substances [4]. The problem of realizing hermetic feedthrough technology is also relevant to other devices that require hermetic encapsulation such as solar cells [5], supercapacitors [6], batteries [7], and OLEDs [8].

There is a growing interest in the use of polymers as encapsulation materials, as they offer reduced weight and manufacturing costs. Polymer encapsulations are advantageous as they could be mass-produced via injection molding, and as a result, have already become more widely used as a replacement for metal components in other industries [9]. This would significantly decrease production costs and thus make this technology more accessible to recipients who would derive considerable benefit but for whom the current technology is prohibitively expensive. Reviews by Qin et al. [10] and Jiang and Zhou [11] outline the success to date with using polymers as an encapsulation material in implantable devices compared to other materials, as well as difficulties associated with their use. The main issue is that polymers are relatively permeable and are susceptible to high moisture absorption, making them unsuitable for long-term use [12]. In addition, the formation of a secure hermetic seal between a polymer and a metal conductor remains a challenging task. Polymer implants have successfully been produced using simple, low-voltage circuits [11], however when the number of individual conductive pathways is large, the problem of achieving hermeticity becomes even more challenging. A scalable technology for producing hermetic feedthroughs that is suitable for use with injection molded polymer components and which overcomes the aforementioned problems is required to realize the benefits of the polymer encapsulation.

This work aims to develop a method of forming electrical feedthroughs into an injection molded polymer encapsulation which may be scaled up to enable larger feedthrough capacity as advances in the capability of implantable devices inevitably occur. For our study, we chose polyetheretherketone (PEEK) as the polymer of interest because of its combination of properties, including its relatively low water vapor transmission rate (WVTR) compared to other polymers such as PET, PES and PLA. We have

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demonstrated in previous work that the WVTR of PEEK can be further reduced to 1% of its original value through the application of thin film barrier coatings [13]. PEEK is a semi-crystalline thermoplastic polymer that is chemically inert due to the delocalization of the electrons over the whole macromolecular structure [14]. This resonance-stabilized structure makes PEEK not only highly resistant to chemicals but also to high temperatures and gamma irradiation [15]. The polymer also shows mechanical toughness, good biocompatibility [14] and is suitable for injection molding [16]. Furthermore, the encapsulation bond strength and the surface properties of PEEK can be adjusted by applying plasma treatment to PEEK with CH_4 and O_2 gases [17,18,19]. Since moisture is the most active agent in the body and in the environment that causes degradation of devices, methods for testing the rate of water penetration are required to investigate the limits to hermeticity of the feedthroughs produced in this study.

2. Materials and methods

The feedthroughs fabricated for this experiment used either sputtered thin film silver conductors or nichrome wires. Silver and nichrome were selected as neither metal oxidizes readily when heated in air. The feedthroughs were prepared on flat PEEK strips, laser welded to another PEEK strip or alternatively, on prototype encapsulations which were laser welded to a lid.

2.1. Preparation of the laser welded feedthroughs

Feedthroughs were prepared using sputtered conductors. A polyimide sheet (thickness 100 um) was used to create a shadow mask for the sputtering process. Slits (width 100, 250, 500, 1000 and 2000 µm) were ablated into the mask using an Excimer KrF-laser (248 nm, 10 mJ, 300 Hz). An Ag-metal thin film (thickness 100 nm) was then sputtered through the mask onto the underlying PEEK (50 W Dc, 110 V, 5 min). Both PEEK strips and the bases of PEEK encapsulations were fabricated using PEEK with 150 ppm of Lumogen®, an additive used to increase the absorption in the light in the infrared range. Ag tracks were deposited by sputtering from a silver target (99.995% pure) using an AJA International ATC 1800 F sputtering system at an operating pressure of 3 mTorr of argon.

To form the feedthrough, a layer of PEEK was then welded on the top of the PEEK/Lumogen®-Ag substrate using a JK100 fiber laser (1070–1090 nm, JKLaser), with the beam directed vertically downward such that it passed through the lid and was absorbed by the Lumogen®-containing base to cause heating at the interface between the base and lid. Both PEEK strips (Fig. 1) and encapsulations (Fig. 2) with Ag tracks of approximately 540 µm (StdDev = 19) were fabricated using this method. The laser parameters used for welding the PEEK/Lumogen®-Ag-PEEK feedthroughs were: power 10 W, focal length 160 mm, speed 10 mm/s, spot size 100 µm, wobble 0.5 mm radius, frequency 1 kHz, pressure 1.8 bar, 2 scans.

Feedthroughs were also formed on the encapsulations using wires as the conductors. Nichrome wires of 20 µm and 100 µm diameter were placed on the bottom part of the encapsulation and the same process and parameters were used to form the feedthroughs as for the sputtered feedthroughs. A sealed package with a nichrome wire feedthrough is shown in Fig. 2.

2.2. Mechanical strength—shear stress test

The PEEK strips shown in Fig. 1 were used for mechanical tests. The PEEK strips were held in place using lap shear grips and attached to the digital force detector (Instron 5567 Computerized Universal Testing Machine, 2.5 N–30 kN). The data was collected as a real-time force graph.

2.3. Electrical resistivity measurements

A modified configuration of the flat strips with only a small PEEK top-layer was used for electrical resistivity measurements so that both ends of the silver track were exposed (Fig. 3). The two-terminal resistance was measured across the length of the track (15.16 mm) using a Kiethley 617 electrometer and the two terminal method for two similar sample arrays, each containing PEEK–Ag feedthroughs with Ag-conductors of 0.10, 0.25, 0.50, 1.0 and 2.0 mm in width before and after laser sealing to another PEEK strip. The resistivity of the wires in the encapsulations shown in Fig. 2 was measured before and after sealing to confirm that the pathway was still conductive.

2.4. Hermeticity measurements

The hermeticity of the samples was studied by a mass loss method [20, 21]. A drop of water was placed inside a PEEK enclosure as shown in Fig. 2, then laser-welded using the method outlined in Section 2.1. The mass of the PEEK enclosure was measured prior to sealing to obtain a measurement of the empty enclosure's mass, and then again after sealing to determine the starting mass of the water inside the enclosure. The samples were stored in a desiccator and their mass loss was monitored over time to determine the water leakage through the feedthroughs into the encapsulation. For comparison, PEEK encapsulations with 20 µm and 100 µm wire feedthrough, and with a sputtered silver tracks of width 540 µm as shown in Fig. 2 were used. PEEK encapsulations without feedthroughs were used as a control.

3. Results

3.1. Mechanical strength

The results for the maximum load before failure using the Instron are shown in Table 1. The samples showed a maximum load

Fig. 1. PEEK strips. Left: top-view (top) and side-view (bottom) schematic of PEEK strips consisting of a base layer containing Lumogen on which silver tracks have been sputtered, and a PEEK layer laser-welded on top. Middle: PEEK strips after laser joining. Right: microscope image of sputtered Ag track on PEEK substrate.

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