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Carbon based resistive strain gauge sensor fabricated on titanium using micro-dispensing direct write technology

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ABSTRACT

Carbon based resistive strain gauge sensor suitable for medical implant technology has been directly fabricated on a titanium test-plate using Micro-Dispensing Direct Write (MDDW) technology. A 3.5 μm biocompatible dielectric layer of parylene C was initially coated on the titanium test-plate. Commercially available screen-print carbon conductive paste was deposited on the parylene C and cured at 80 °C for 3 h; this was to ensure the physical properties and chemical integrity of the parylene C layer was maintained, whilst meeting the electrical conductivity curing requirements for the carbon tracks. The novel integrated strain sensor was experimentally tested and found to have a gauge factor of 10 making it approximately 5 times more sensitive than a commercially available metal foil strain gauge glued to the same titanium plate.

1. Introduction

There is an increase in the research activity of customised medical implants using additive manufacturing (AM) technologies [1,2]. AM implants are usually fabricated from one material and there is no integrated sensor for feeding back the mechanical performance of the implant. Often there can be a mismatch in the mechanical properties between the implant and the host bone tissue, which may lead to the loosening of the implant over time, referred to as "stress shielding" [3,4]. Presently X-ray with computer topography is used to image the implant and host bone tissue, to determine any mismatch but cannot be used for real time monitoring [5].

A mechanical parameter for monitoring the performance of the implant is strain, which can be measured in real time using an attached strain gauge sensor [6]. The strain gauge is normally glued to the implant and it is assumed the strain gauge has the same deformation properties as the adhesive mounting. The strain is determined by the change in resistance of the strain gauge caused by the deformation of the resistive sensing grid. The technique of gluing the strain gauge to the implant can lead to delamination between the strain gauge and the implant particularly in a biological environment leading to premature failure; often more common when monitoring over an extended period of time [7].

The fabrication of low conductivity carbon-based strain gauges have been reported with gauge sensitivity ranging between 2.48 to 59, which is greater than obtained from commercial gauges with comparable geometry [8–11]. The very high gauge factors were obtained from carbon nanotube based sensors making the cost of the fabrication process very high [9]. Work has also been reported on carbon strain gauges consisting of conductive single-walled carbon nanonets (SWCNN) sensing grids encapsulated between two parylene C layers to ensure biocompatibility [8,12]. However, adhesives were still required to attach the film-like strain gauges on to the test surface. With the increasing sophistication of implant fabrication using AM there is a need to integrate 'bespoke' sensitive strain sensors as part of the medical implant.

The method presented in this research work used a computer programmable micro-dispensing direct write (MDDW) technology to fabricate a sensitive strain gauge directly on to a metal test-plate without the use of adhesives for medical implant application. The strain gauges were fabricated using a low conductivity (400 Ω/sq/mil) carbon paste to form the sensitive sensing grid directly deposited on a layer of parylene C, which was first coated on the surface of a titanium test-plate. A titanium test-plate was used to simulate the medical implant material. The novel approach of using parylene C as the insulation layer between the strain gauge and the titanium surface offers the advantage that parylene C is already FDA-approved for medical applications. Moreover, parylene C has a low Young's modulus (~4000 MPa) making it

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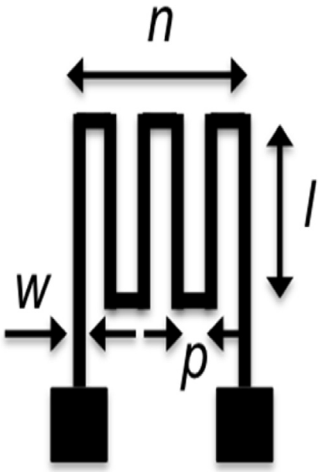

Fig. 1. The layout of the miniature resistive strain gauge.

Table 1
The dimensions of the designed resistive strain gauge.

n	l	p	w
2	5 mm	0.5 mm	175 ± 12 μm

mechanically very suitable as the insulating layer between the strain gauge and the titanium test-plate surface [10].

2. Experimental

2.1. Fabrication process

The experimental carbon based strain gauges were fabricated using nScrypt 3Dn-300 (Orlando, FL, USA) micro-dispensing direct write (MDDW) system, which allows the extrusion of paste material with viscosity in the range from 1 to 1,000,000 mPa s through a fine ceramic nTip nozzle (50 μm internal diameter). The nScrypt 3Dn-300 was equipped with a SmartPump using a patented valve that controlled the start and stop of the carbon paste flow. The valve incorporates a unique suck-back action at the end of each dispensing operation to prevent the clogging of the paste in the nozzle tip, ensuring a clean start for the next dispensing action [13].

Low cost commercial screen printable carbon paste with a viscosity range from 210 to 260 Pa·s was chosen and pre-loaded in a syringe connected to the pressurised SmartPump dispensing valve. The paste deposition process parameters included the dispensing height, dispensing speed, and material feed pressure. These were optimised to obtain a constant track width throughout the printed pattern of the strain gauge.

A miniature strain gauge Fig. 1 was designed to have a high gauge factor using the low electrical conductive carbon paste. The dimensions of the strain gauge are given in Table 1, where *n* is the number of loops, *l* is the gauge length, *p* is the gap between the sensing grids, and *w* is the track width. The design was loaded into PathCAD and exported as a path script file to control the dispensing mechanism of the nScrypt machine.

The carbon-based strain gauge pattern was directly written on the 3.5 μm thick layer of parylene C (Para Tech Coating LTD., Northampton, UK), which had been first coated on the titanium test-plate using chemical vapour deposition (CVD). The carbon based strain gauge structure was post cured in a box oven at a relatively low temperature of 80° C for 3 h to firstly drive off the solvent making up the conductive carbon paste to ensure a stable electrical resistive grid, and secondly to ensure that the electrical and mechanical properties of the parylene C were not modified.

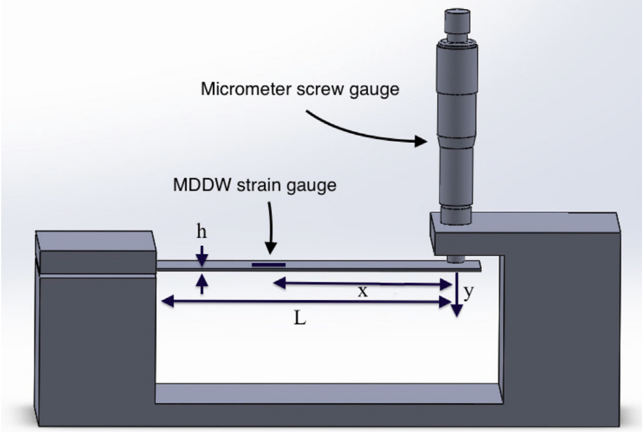

Fig. 2. Schematic of the cantilever test rig for measuring the gauge factor of the Integrated MDDW strain gauge.

2.2. Mechanical testing

A cantilever beam jig was used for measuring the strain performance of the sensor. The titanium test-plate was clamped to one end of the jig and the other end of the test-plate was deflected using a micrometer screw gauge as shown in Fig. 2. The corresponding strain ε of the strain gauge at the location "x" was calculated using the Eq. (1) [9]:

$$\varepsilon = \frac{3xyh}{2L^3} \tag{1}$$

For these measurements x = 22 mm (the distance between the strain gauge sensor and the position where the bending force was applied); L = 68 mm (the distance between the clamped end of the titanium test-plate and the position where the bending force was applied); h = 1 mm (the thickness of the titanium test-plate), and y the deflection in 0.25 mm steps of the titanium test-plate using the micrometer screw gauge.

With the application of the strain using the cantilever test-jig the corresponding change in the electrical resistance of the strain gauge was measured using a Fluke 289 true-RMS digital logging multi-meter. The strain gauge performance was quantified using the gauge factor (GF) definition, which can be expressed as Eq. (2), the unit change in resistance per strain:

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

The above strain measurement method was initially validated using a commercial strain gauge with a known gauge factor.

3. Results and discussion

It was found that the most important nScrypt MDDW process parameters that control dispensing material flowrate were material feed pressure, dispensing height and dispensing speed. Initially, the three parameters were found using 3-level full factorial design of experiments (27 sets with 5 repeats) by monitoring the track quality of dispensed silver paste (DuPont 5025). Feed pressure was found to be the most sensitive parameter for final tuning the low conductive carbon paste (DuPont 7082) deposited track quality. A schematic diagram of dispensing mechanism using the nScrypt SmartPump is shown in Fig. 3.

Fig. 4 shows the micrograph of carbon paste (DuPont 7082) patterns as a function of material feed pressure of 8psi, 10psi, 12 psi and 14psi. For test patterns where the feed pressure was below 12psi, the tracks were inconsistent due to discontinuous deposition being