Production of Organometallic Polymer-Based Biomaterials by Laser Two-Photon Polymerisation

E. BALČIŪNAS[1,2], S. BALDOCK[2], D. BALTRIUKIENĖ[1] and J. G. HARDY[2]
[1]Institute of Biochemistry, Life Sciences Centre, Vilnius University, Vilnius, Lithuania
[2]Department of Chemistry, Lancaster University, Lancaster, United Kingdom
ev.balciunas@gmail.com, johnhardyuk@gmail.com

ABSTRACT
Laser two-photon polymerisation is a 3D printing technique based on the process of two photon absorption, where a photosensitive molecule becomes a radical upon absorbing two photons with double the wavelength of its absorption peak. By moving the sample relative to the laser focal point, 3D structures with sub-micron features can be fabricated from a variety of materials.
Here, we present a novel organometallic polymer biomaterial composed of aluminium isopropoxide, methacrylic acid and 3-methacryloxypropyltrihydroxysilane. We describe the preparation, fabrication, development aspects of this material and characterise some structures fabricated directly from computer-aided design (CAD) files using scanning electron microscopy (SEM).

KEYWORDS: Biomaterials, Laser Two-Photon Polymerisation, Micro 3D Printing, Microfabrication, Organometallic Polymers.

1. INTRODUCTION

3D printing technologies have been on a rise since their inception - both in terms of the number of users and system manufacturers. Today there are hundreds of companies manufacturing and selling 3D printing systems from the simplest ones that cost less than €70 [1] to multi-million € custom-made systems. For example, in early 2014, the private spacecraft company SpaceX launched its Falcon 9 rocket with a 3D-printed main oxidizer valve body in one of the nine Merlin engines [2].

Various 3D printing techniques have been developed since the first report of a UV-based 3D printer [3] - stereolithography [4], fused deposition modelling [5], selective laser sintering [6], inkjet printing [7], selective laser melting [8], electron beam melting [9], laminated object manufacturing [10] and laser two-photon polymerisation [11]. 3D printing techniques vary greatly in terms of build volume, resolution, speed and processable materials.

Laser two-photon polymerisation is a technique based on the two-photon absorption process predicted by M. Goeppert-Mayer in 1931 [12]. When a photosensitive molecule is placed in a field with high photon density, where the wavelength of the photons is twice that of the absorption peak of the molecule, two photons can be absorbed simultaneously, causing the molecule to lose an electron and become a radical. The process only takes place over a certain intensity threshold and by working close to the threshold, features smaller than the wavelength used can be fabricated. The high photon density is created by using a high peak power, ultra-short pulse laser and tightly focusing the beam within a photosensitive material.

By changing the position of the laser focal point in relation to the sample, a 3D structure is written. After fabrication, unexposed parts of the material are washed out using a solvent (Fig. 1).

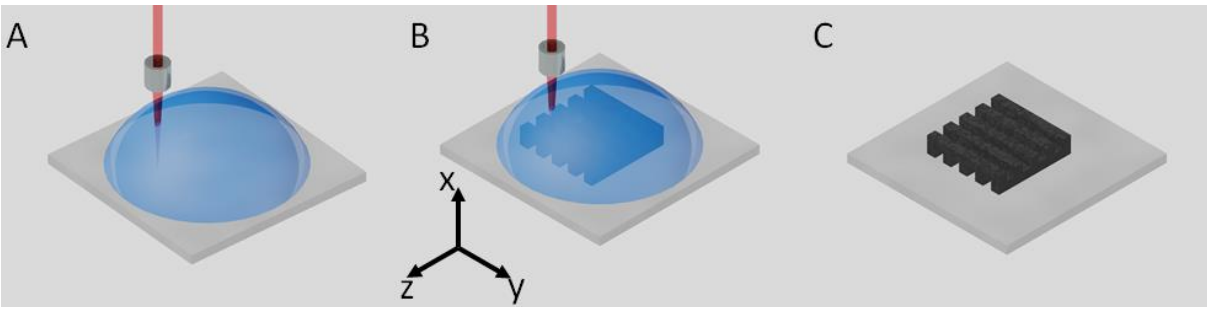

Figure 1: A – the laser beam is tightly focused in a photosensitive material. B – two-photon absorption takes place and radical polymerisation is initiated in the focal point, which is being positioned relative to the sample. A 3D structure is written. C – Unexposed parts of the material are washed out and the structure is revealed.

Various materials can be structured using two-photon polymerisation systems – PEG-DA [13], commercially available organically modified ceramics (ORMOCER®) and epoxy-based SU-8 [14], type I collagen [15], bovine serum albumin [16], hyaluronic acid [17] and others. The materials can be doped with drugs, like gentamicin sulphate [18].

A widely investigated group of materials are hybrid organic-inorganic polymers, where metal alkoxides are hydrolysed, chelated and crosslinked with silicon oxide containing acrylates. To date, hybrid materials containing zirconium [19], titanium [20], germanium [21] and vanadium [22] have been investigated.

Here, we investigate a novel hybrid organic-inorganic material containing aluminium. We describe the preparation, structuring and characterisation of this material, discussing its possible applications as a biomaterial.

2. EXPERIMENTAL PROCEDURES

2.1 Material preparation

Aluminium isopropoxide (AIP) was dissolved in toluene at a 1 to 10 m/m ratio and ultrasonicated for 30 min. Subsequently, methacrylic acid (MAA) was added to the solution at a 1:1 AIP:MAA molar ratio and stirred for 15 min. In parallel, 3-methacryloxypropyltrimethoxysilane was hydrolysed to 3-methacryloxypropyltrihydroxy-silane (MAPTHS) using 0.1 M HCl at a 10:1 V/V ratio for 15 min. After hydrolysis, the two mixtures - AIP/toluene/MAA and MAPTHS/HCl were mixed together for 15 min with 1:1:9 AIP:MAA:MAPTHS molar ratios. Finally, 1 % (w/w (AIP + MAA + MAPTHS)) of photoinitiator (4,4′- bis(diethylamino)benzophenone) was added and stirred in the dark for at least 30 min. All materials were purchased from Sigma-Aldrich.

2.2 Polymerisation

The material was drop-cast onto glass slides, covered to protect from ambient light and left in a fume hood to allow the toluene to evaporate. Next, the slides were glued on to the Nanoscribe (Photonic Professional GT, Nanoscribe GmbH, Germany) sample holder and placed in the system, material side-up. Immersion oil was applied in the case of 63x 1.4 NA objective lens between the slide and the lens. Stereolithography (.STL) files were either created using CAD software (Autodesk AutoCAD) or downloaded from the web [23], then sliced using proprietary Nanoscribe software (DeScribe 2.3.3). Hatching and slicing distances in X, Y and Z coordinates were set to 0.1 µm. Laser scanning speed was set between 2 and 10 mm/s and the laser power was set between 20 - 100 % (corresponding to 10 - 50 mW). After polymerisation, the samples were developed in toluene for at least 15 min and dried under ambient conditions.

2.3 Structure characterisation

The samples were coated with a 10 nm layer of gold using a sputter coater (Q150 RS, Quorum Technologies) and subsequently observed using a SEM (JSM 7800F, JEOL) operating at 10-15 kV.

3. DISCUSSION OF RESULTS

3.1 Material preparation

The preparation procedure for the aluminium hybrid is comparable to that of other hybrid materials. It is a clear yellowish liquid (colour due to the presence of the photoinitiator) that becomes a solid-like gel after evaporation of the solvent. Gelation reduces structural distortions that would arise in liquids due to vibrations, diffusion and stage movement in some laser two-photon polymerisation systems.

3.2 Polymerisation and structure characterisation

To assess the structurability of the material, suspended lines with varying laser power and scanning speed were written on top of bulky support structures (Fig. 2). The support structures were fabricated using 10 mm/s scanning speed and 20 % (10 mW) laser power. It was observed that the material was likely to deform – the sides and corners of support structures tended to shrink, the suspended lines were more likely to stick together and the cube on the top left corner of the structure, fabricated for unambiguous sample positioning in SEM, tended to shrink towards the top. 10 mW power was insufficient to crosslink single suspended lines even at 2 mm/s scanning speed. However, fabrication of bulk structures with multiple parallel scans was best achieved using 10 mm/s scanning speed and 20 – 25 % (10 – 12.5 mW) laser power. No microexplosions or burning were observed in fabricating these line arrays, indicating a wide fabrication window – the power interval between polymerisation threshold and photodamage. This is an important parameter when considering fabrication of large-scale structures.

Sub-micron resolution was achieved when fabricating suspended lines (Fig. 3 B). They were reproducibly fabricated using the 63x 1.4 NA oil immersion objective lens. High aspect ratio structures with suspended features were easily materialised as well (Fig. 3 A).

Future studies will be aimed at characterising the chemical structure of the polymer, its mechanical, electrical properties and biocompatibility. Other proportions of AIP:MAA:MAPTHS could yield even better quality structures, so a screening study might be of use.

We believe the material described here might find use in fields like tissue engineering, photonics, microelectromechanical systems (MEMS) and microfluidics.

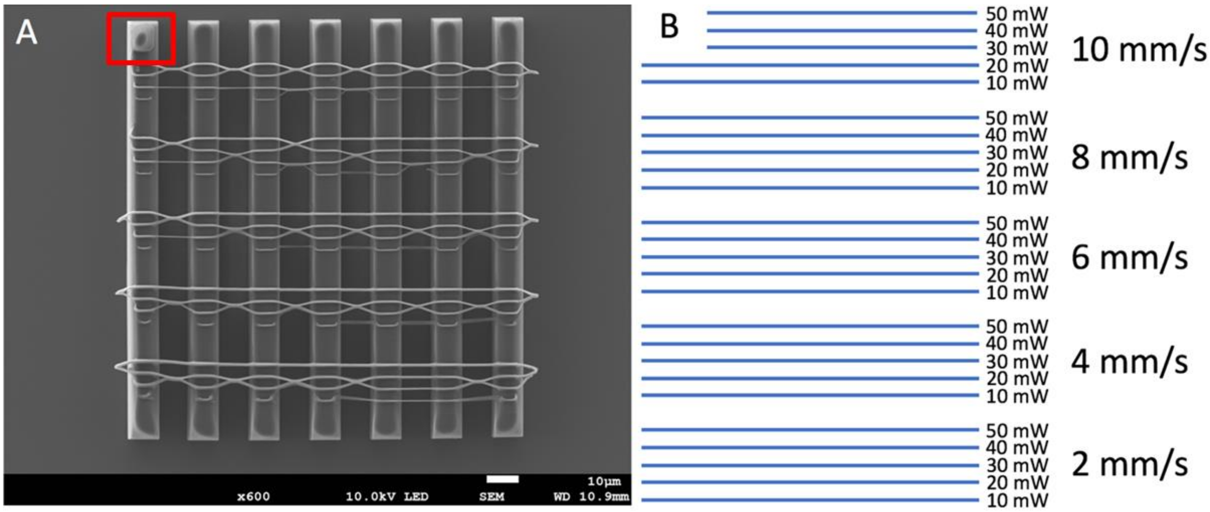

Figure 2: A - support structures with lines fabricated on top. Red rectangle shows the cube fabricated for unambiguous positioning in SEM. B picture shows the arrangement of lines with varying scanning speeds between 2 – 10 mm/s and laser power between 10 and 50 mW.

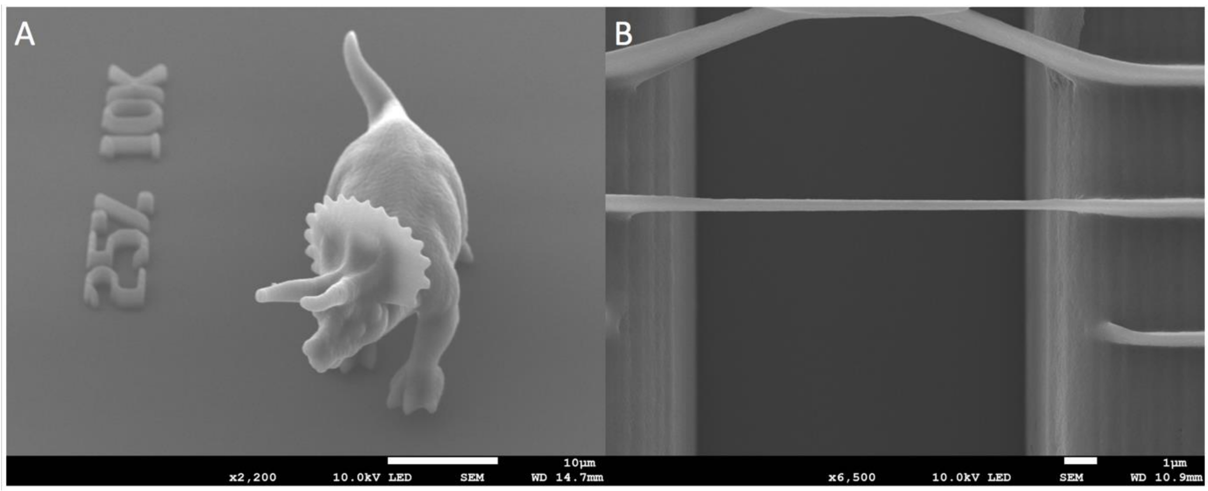

Figure 3: A - a 3D triceratops with high aspect ratio horns and tail made from the aluminium containing hybrid material. 25 % (12.5 mW) laser power and 10 mm/s scanning speed were used. B – Suspended line with sub-micron width.

4. CONCLUSIONS

A novel organometallic polymer material containing aluminium has been developed. Structures fabricated using laser two-photon polymerisation are well in accord with CAD input with minor deformations. Suspended lines with a width of less than a micron can be reproducibly fabricated using a 63x 1.4 NA oil immersion lens on a Nanoscribe Photonic Professional GT two-photon polymerisation system. The material presented here shows promise in fabricating micro-scale objects, such as scaffolds for tissue engineering or photonic crystals, microoptical elements, MEMS, microfluidics and others.

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