Materials and Design 154 (2018) 326–339

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Angle defines attachment: Switching the biological response to titanium interfaces by modifying the inclination angle during selective laser melting

Avik Sarker [a,b], Nhiem Tran [c], Aaqil Rifai [a], Joe Elambasseril [b], Milan Brandt [a,b], Richard Williams [a,b,d,1], Martin Leary [a,b,1], Kate Fox [a,b,*,1]

[a] School of Engineering, RMIT University, Melbourne, Victoria 3001, Australia
[b] Centre for Additive Manufacturing, RMIT University, PO Box 2476, Melbourne, Victoria 3001, Australia
[c] School of Science, RMIT University, Melbourne, Victoria 3001, Australia
[d] BioFab3D, St Vincent's Hospital, 29 Regent Street, Fitzroy VIC 3065, Australia

HIGHLIGHTS

- Ti6Al4V implants were successfully fabricated with different inclinations (0, 45 and 90 degrees).
- Partially melted particles adhering to the surface affect implant surface topography, morphology, roughness, and wettability.
- Matlab program was developed for counting the cells type on different inclined surface.
- Spindle cell number was found to increase at higher inclination angles (90 degrees).
- Minimal surface treatment required if the inclination angle is used to develop the implant surface.

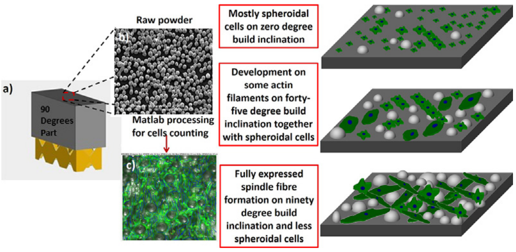
ARTICLE INFO

Article history:
Received 3 March 2018
Received in revised form 8 May 2018
Accepted 19 May 2018
Available online 22 May 2018

Keywords:
Additive manufacturing
Selective laser melting
Inclination angle
Cell attachment
Biomedical implant

GRAPHICAL ABSTRACT

Selective Laser Melting (SLM), a powder bed fusion technology which has been applied for building different inclined Ti6Al4V part fabrication for biomedical implant. Ti6Al4V SLM part built with higher inclination angle such as 90 degrees revealing the rough surface texture adhering the higher amount of partially melted particles has greatly influenced the increasing the number of spindle cells and their dimension with less amount of spheriodal cells.



ABSTRACT

Developing patient-specific biomedical implants for clinical application requires the integration of material science, manufacturing engineering, and biology. As selective laser melted (SLM) metallic additive manufactured implants become common, a key, but overlooked design parameter is its inclination angle. In this study, we have fabricated Ti6Al4V implants at three different inclination angles (0, 45 and 90 degrees) reporting the relationship between cell attachment, surface topography and surface chemistry at each angle. During the SLM process, we show that as the inclination angles increase, there is a corresponding increase in the number of partially melted particles adhering to the surface, greatly affecting the surface topography, morphology, roughness, chemistry, and wettability of the implant. In order to validate the approach, the effect of surface properties on cell fate was determined. In each case, the overall viability of Chinese hamster ovarian cells (CHO) was found to be statistically indistinguishable; however, the number of spindle cells and their dimension were found to increase significantly at higher inclination angles. This

---

[*] Corresponding author at: School of Engineering, RMIT University, Melbourne, Victoria 3001, Australia.
E-mail address: kate.fox@rmit.edu.au (K. Fox).

[1] These authors contributed equally.

https://doi.org/10.1016/j.matdes.2018.05.043

work demonstrates a novel approach for combining SLM technology in manufacturing metallic biomedical implants and provides a novel insight in case of switching cell titanium interface by modifying one process parameter, inclination angle, during rapid prototyping process.

1. Introduction

Metals and metal-alloys have a long history of application as bone, cardiovascular implants [1–5]. Metal and metal alloys including magnesium, iron, titanium, tantalum, titanium nickel, stainless steels, cobalt (Co) based alloys (CoCrMo) have been applied as potential bone graft, cardiovascular stents [6–11]. Among a wide variety of different metals used for biomedical implants, titanium and its alloy has been used as an effective implant material due to its excellent biocompatibility, strength to weight ratio, corrosion resistance, toughness, and bio-inert oxide surface [12–16]. The titanium alloy presented this paper Ti6Al4V covers about 50% industrial applications of all titanium [17].

Rapid prototyping or additive manufacturing (AM) makes possible the fabrication of biomedical implants with hitherto unprecedented structural complexity and prescribed microstructure and macrostructure [18–21]. Additive manufacturing offers numerous commercial technologies for the fabrication of robust components via a layer-by-layer design associated with a computer model [22–24]. This control over the shape, size and mechanical properties enables the investigation of individual implant parameters such as porosity, pore size, shape and permeability [25]. Metal based AM is being widely used for tissue engineering applications for manufacturing patient-specific orthopaedic, cardiac implants, [1,26–32] and the biological performance of synthetic bone grafts [25].

Selective laser melting (SLM) is a Metallic AM (MAM) process that creates parts by scanning powdered materials using the thermal energy supplied by a focused and computer controlled laser beam based on a digital representation of the intended implant geometry. SLM is a layer-by-layer material addition technique that allows the generation of complex 3D parts by selectively melting successive layers of metal powder [23]. With reference to commercial MAM technologies, SLM is characterized by medium productivity, good repeatability and medium to high surface quality [18]. The SLM process was reported to be capable of fabricating implants of several pure titanium and titanium based alloys for implants such as Ti6Al7Nb [33], Ti-24Nb-4Zr-8Sn [24],Ni-Ti [34], Ti-13Nb-13Zr [35] other β titanium alloys [36] and most importantly Ti6Al4V [37,38]. Recently, it was reported that SLM has the ability to fabricate porous bio-inert Ti6Al4V structures with high control and reproducibility in terms of their morphological and mechanical properties [39] and showed excellent biocompatibility [40].

Significant research on the design of cellular lattice structures has shown potential for controlling dimensional accuracy, mechanical properties and associated biocompatibility [24,41–43]. The final surface topography, morphology, chemistry, and wettability of the implants can be altered to adjust the interaction between the implant and the host tissue [44–48]. These properties are dependent on the associated SLM process parameters [49–52]. Laser power, scanning speed, scanning pattern, hatch spacing, layer thickness, powder bed temperature and working atmosphere are the most critical processing parameters for the SLM process, and several groups focused their research on optimizing these parameters for the final desired parts [53–56].

We have previously shown that the mechanical properties of SLM manufactured Ti-6Al-4 V and AlSi12Mg lattice structures can be effectively manipulated to match tissue specific parameters [57,58]. Cellular lattice structures fabricated by SLM process are the combination of numerous strut elements, each with specific inclination angle to the SLM platen. Here, for the first time, we report the relationship of the inclination angle of the implant of 0, 45 and 90 degrees with their surface morphology, surface wettability, and surface chemistry; and, demonstrate that these parameters have a direct relationship with biocompatibility, cell attachment and cell morphology. This work will have significant impact on the design and fabrication of these materials for biomedical applications and the fabrication of the next generation of just-in-time, patient specific implants.

2. Materials and methods

2.1. Sample preparation

Inclination samples ($10 \times 10 \times 2$ mm^3) were fabricated by selective laser melting (SLM) with a SLM250HL machine (SLM Solutions, Germany) with a variable power 400 W fibre laser. The SLM powder was titanium alloy Ti-6Al-4 V, with average particle size of approximately 40 μm. Test specimens were manufactured with the following process parameters: laser power, $P = 100$ W, scanning speed, $v = 375$ mm/s, layer thickness, $t = 30$ μm, hatch spacing, $h = 0.12$ mm and focal offset, $f = 0$ mm. These parameters correspond to: volumetric energy density, $E_v = 68.5$ J/ mm^3 where $E_v = P/vht$ and provide high geometric quality with fully dense structure. The mechanical properties of (ultimate tensile strength, yield strength, and modulus of elasticity) of Ti64 SLM parts were $\sigma_{UTS} = 1027$ MPa, $\sigma_{y0.2\%} = 970$ MPa, and $E = 113$ Gpa, respectively. These parameters were used in the manufacture of implants with inclination angles of 0, 45 and 90 degrees. Support structures were removed from the struts and struts were cleaned using standard cleaning methodology of sequential sonication in acetone, methanol and isopropanol and dried under a steady flow of nitrogen gas.

Samples were analysed before and after treatment for comparative assessment and accuracy of data.

2.2. Characterisation

2.2.1. CT scan

The SLM built inclined surfaces at different angles were analysed using General Electric Phoenix v|tome|x s 240 X-ray Computed Tomography (CT). Key feature of interest is the surface finish of the parts. The CT scanned parts were of $10 \times 10 \times 2.0$ mm^3 and the CT scans were performed using 190 KV and 50 μA for X-ray generation, including beam filters of 1 mm tin and 0.1 mm copper, at a resolution of 9 μm. To reduce the beam hardening effect, two copper filters of 0.1 mm in thickness were used which block the low energy beams. The projected X-ray images were acquired at 333 ms per image, with 2000 images in stepwise rotation of the sample.

2.2.2. Surface profile analysis

Digital Microscope VHX-500 (Keyence, Japan) was used for optical photos, 2D profile and 3D profile analysis.

2.2.3. Surface roughness analysis

Roughness was assessed using a XP-2 Stylus Profiler (Ambios Technology, Inc.,USA) of 3D scanning at a force 1.0 mg, scan speed of 50 μm/s with X scan size 1000 μm, Y scan size 200 μm with 5 traces having 50 μm Y spacing. Each sample was repeated 5 times. Data was analysed using Gwyddion image processing software.

2.2.4. Surface wettability analysis

Contact angle measurements were carried out using a contact angle measuring system (OCA-20 contact angle meter and tensiometer,