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Review

Metallic powder-bed based 3D printing of cellular scaffolds for orthopaedic implants: A state-of-the-art review on manufacturing, topological design, mechanical properties and biocompatibility

X.P. Tan [*,1], Y.J. Tan [1], C.S.L. Chow, S.B. Tor, W.Y. Yeong

Singapore Centre for 3D Printing, School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore

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ABSTRACT

Metallic cellular scaffold is one of the best choices for orthopaedic implants as a replacement of human body parts, which could improve life quality and increase longevity for the people needed. Unlike conventional methods of making cellular scaffolds, three-dimensional (3D) printing or additive manufacturing opens up new possibilities to fabricate those customisable intricate designs with highly interconnected pores. In the past decade, metallic powder-bed based 3D printing methods emerged and the techniques are becoming increasingly mature recently, where selective laser melting (SLM) and selective electron beam melting (SEBM) are the two representatives. Due to the advantages of good dimensional accuracy, high build resolution, clean build environment, saving materials, high customisability, etc., SLM and SEBM show huge potential in direct customisable manufacturing of metallic cellular scaffolds for orthopaedic implants. Ti-6Al-4 V to date is still considered to be the optimal materials for producing orthopaedic implants due to its best combination of biocompatibility, corrosion resistance and mechanical properties. This paper presents a state-of-the-art overview mainly on manufacturing, topological design, mechanical properties and biocompatibility of cellular Ti-6Al-4V scaffolds via SLM and SEBM methods. Current manufacturing limitations, topological shortcomings, uncertainty of biocompatible test were sufficiently discussed herein. Future perspectives and recommendations were given at the end.

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* Corresponding author.
E-mail address: xptan@ntu.edu.sg (X.P. Tan).
[1] The first two authors contribute equally to this paper.

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1. Introduction

Manufacturing places broad emphasis on speed, accuracy, flexibility, and minimizing waste nowadays. This is why there have been increasing interests in the area of additive manufacturing, most commonly known as three-dimensional (3D) printing. While conventional manufacturing methods such as machining are rooted in removal of material from bulk form (i.e. subtractive manufacturing), the essence of 3D printing is to build up an object layer by layer adding material only where necessary [1,2]. Near-net-shape capability, or printing parts close to the designed profile, with the exception of support structures, uses as little excess material as possible. This drastically reduces by-product waste as compared to subtractive manufacturing. This in turn reduces the lead-time and tooling required for product completion, leading to savings in production costs [3]. The capability of 3D printing extends to cover a wide range of material types, including polymers, ceramics, metals, etc. [4,5].

One mainstream direction for 3D printing is that of biomedical applications, specifically in creating scaffolds for medical implants [6–10]. This paper focuses on the fabrication of scaffolds for orthopaedic (bone) implants by utilizing powder-bed based metallic 3D printing [11]. The first and foremost requirement for the orthopaedic implants is to fill 3D defect cavities. Traditionally, metallic orthopaedic implants have been produced by investment casting or forging. Although different prosthetic implant sizes can be produced through the conventional means, they cannot achieve the same level of patient-customization as 3D printing. With 3D printing, the shape and design of implants can be individualised to ensure best fit to their recipients. This can even be done by direct data input from computed tomography (CT) or magnetic resonance imaging (MRI) scans. Beyond efficiency, the near-net-shape capability of 3D printing drastically reduces wastage of material as compared to traditional subtractive manufacturing methods. This will help to balance out the equipment setup costs in the long run [12].

Hutmacher derived four essential characteristics of a biodegradable bone scaffold, which were found to be transferrable to a metallic orthopaedic implant as well: (i) biocompatibility leading to a natural cell growth rate on the scaffold; (ii) similar mechanical characteristics with existing tissue at implant area; (iii) suitable porosity for cell ingrowth and channels for nutrient and waste transportation; (iv) attractive surface morphology for cell attachment and proliferation [13]. Biocompatibility of a scaffold mainly depends on the materials used and the fabrication process. Titanium and its alloys, and various other metals, such as cobalt chromium (CoCr) alloys and stainless steel 316L (SS316L), are known to have excellent biocompatibility [14]. While this review will be focused on titanium alloys, which were most widely used for orthopaedic implants because they have a lower modulus of elasticity that is closer to that of host bone and are more biocompatible than CoCr alloy or SS316L. On the other hand, titanium alloys are notch-sensitive, which predisposes it to cracks if the implant is not well supported [15].

In addition, it is important for an orthopaedic implant to mimic mechanical characteristics of bone to maximise its usefulness in the body. Dissimilar mechanical properties between the implant and bone may lead to many undesirable effects. One such phenomenon called stress shielding is caused by the differences in elastic modulus or stiffness, leading to the existing bone being overly relieved of load [16]. This leads to bone resorption which may cause the implant to loosen from the bone [17], which might affect the fixation and longevity of the implant within the body [18]. A solution to this is to use cellular or porous titanium structures, which have closer mechanical properties to actual bone [19]. Another crucial reason to use cellular structures is to mimic the structure of native bone to promote bone regeneration and ingrowth into the implant, which has so far not been observed on solid structures [20,21]. Studies have also shown that the surface types of these implants play a role in regulating bone cell responses and bone healing [22]. Rough surfaces obtained through sandblasting and/or acid-etching are favoured [23]. Chemically modified implant surface by using hydrogen chloride (HCl) and sodium hydroxide (NaOH) also believed to provide a better fixation of the implant and improve the long-term stability of the implant [24].

In general, it is very difficult or impossible to rely on traditional manufacturing methods to craft a cellular structure throughout an orthopaedic implant. 3D printing makes this relatively easy as it is builds up a form layer by layer, including the internal cellular cross-sections. It is hence possible to produce intricate cellular implants tailored to biomedical applications. To produce a useful implant, factors such as topological design of pores, porosity, mechanical properties, and interfacing with natural bone have to be carefully considered [25]. Design of cellular scaffolds can also be made more anatomically-suitable by applying image data from medical databases. This allows satisfactory replication of natural bodily functions such as transport of nutrients and waste [12].

This review is divided into the following four major sections: metallic powder-based 3D printing techniques, hierarchical design of metallic cellular scaffolds, microstructural characterization and mechanical properties, and in vitro and in vivo studies of 3D-printed cellular bone implants. This review will gather findings from across the fields related to 3D printing for bio-implants, and serve to compare the different methodologies used to eventually arrive at the most reasonable direction for each of the above sections. In the first section, the working principles behind two common powder-based 3D printing techniques, selective laser melting (SLM) and selective electron beam melting (SEBM), will be examined and compared. These methods involve using a high energy beam to melt the shape of cross-sections into layers of metallic powder, building layer upon layer into the desired product [26,27]. The advantages and disadvantages of each method with regards to biomedical applications will also be mentioned. The next section will briefly touch on the needs for metallic scaffold implants and present regular and irregular interconnected pore cellular designs. This will lead up to the following section which will present the mechanical behaviour obtained from testing entire cellular structures. A study into the microstructures of these 3D printed cellular structures will be made and the differences resulting from different manufacturing processes will be compared. The final section will look at the performances of 3D-printed bio-implants with regard to in vitro cell culture and in vivo animal testing. Challenges and future perspectives on 3D-printed cellular scaffolds for orthopaedic implants will be given in the end.

2. Metallic 3D printing systems

SLM and SEBM are the two prolific powder-bed based 3D printing techniques for metals nowadays. In both processes, high energy beams are utilized to melt cross-sectional shapes into layers of metal powder [26,28], fusing powder particles into a large form, with each layer representing a “slice” of the final product. After every “slice” is formed, the build platform moves downwards by the distance equivalent to a layer's thickness and a fresh layer of metal powder is uniformly spread on top of it. The process repeats so that the cross-sections build up cumulatively until the build is finished. At the end, the excess,