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Microstructure, defects and mechanical behavior of beta-type titanium porous structures manufactured by electron beam melting and selective laser melting

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ABSTRACT

This study investigates the differences in the microstructure, defects and mechanical behavior of porous structures from a β-type Ti–24Nb–4Zr–8Sn manufactured by electron beam melting (EBM) and selective laser melting (SLM). The phases, size and shape of melt pool, volume and distribution of defects are analyzed and correlated to the compressive mechanical and fatigue properties. Due to different powder bed temperatures, the microstructure of EBM and SLM samples consists of $\alpha+\beta$ phases and a single β phase, respectively. The faster cooling rate during SLM promotes the formation of fine β dendrites, which leads to a higher compressive strength (50 ± 0.9 MPa) and lower Young's Modulus (0.95 ± 0.05 GPa) in comparison to the EBM parts (45 ± 1.1 MPa and 1.34 ± 0.04 GPa respectively). The large defects present within solid strut are likely a result of tin vaporization. The tin vapor is more easily trapped during the SLM process due to a smaller laser spot size and a faster cooling rate. This results in a 10 times increase in the number of defects. These defects have a limited influence on both the static properties and low stresses level fatigue strength, but it causes a reduced and variable fatigue life at high stresses level.

1. Introduction

Recently, the demand for implants has been increasing as more people are suffering from joint problems caused by aging population and obesity [1]. It is therefore becoming necessary to produce high quality, artificial joints in order to reduce the risk of revision surgery. Several desirable requirements, such as customized complex shape to fit the surrounding bone, interconnecting porosity with suitable size to facilitate bone in-growth, high strength and low Young's modulus, are needed to qualify a successful implant [2]. Fortunately, additive manufacturing (AM) techniques such as selective laser melting (SLM) and electron beam melting (EBM) technologies, emerging as advanced manufacturing technologies to build components using powder material via a layer-wise method from 3D CAD models, are capable of manufacturing porous implants with optimal properties to meet these requirements, using medical grade metallic powder materials [3–6]. These AM technologies have attracted increasing interest in the past decade.

Compared to conventional processing methods, SLM/EBM can create complicated geometries (such as porous structures) in a shorter time and with lower cost [7]. The as-fabricated samples typically contain a finer, and often different, microstructure compared to those produced by conventional processing technologies. As such, the SLM/EBM-produced porous components have been reported to exhibit outstanding properties including low density, high strength, toughness and ductility [8–11]. Both EBM and SLM have similar working principle. A focused heat source selectively scans a powder bed. The scanned powder is melted and then rapidly solidifies. Once a layer is completed, the build platform descends by one layer thickness and a new layer of powder is deposited on top. Such a layer-by-layer process continues until the entire component has been completely produced [8]. The main difference between the two processes originates from the heat

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source used; EBM is equipped with a tungsten filament to generate electron beam while SLM uses a laser. In addition, there are difference in the working conditions between the two techniques, including the chamber pressure and the pre-heating procedure. These can significantly alter the microstructure of the samples manufactured by the two technologies [12].

As a result of its density, low Young's modulus and high strength and corrosion resistance, titanium alloys are regarded as the most appropriate implant materials for load bearing applications [13,14]. Currently, the majority of studies on AM-produced titanium alloys have been focused on the processing and mechanical properties of the traditional (α+β)-type Ti–6Al–4V. Although it has been reported that the SLM-produced Ti–6Al–4V porous structures exhibit high biocompatibility, good mechanical properties and good corrosion resistance [15], there is a concern that the toxic elements Al and V in Ti–6Al–4V might lead to allergic reaction and Alzheimer's disease [16]. Furthermore, the large mismatch in Young's modulus between Ti–6Al–4V implants and the surrounding bone can lead to the well-known “stress-shielding” phenomenon [5]. In addition, α′ martensite usually formed in the microstructure of AM-produced Ti–6Al–4V components is detrimental to their ductility and fatigue life [3] and degrades the corrosion resistance as well [17]. Therefore, it is imperative to find alternative titanium alloys to eliminate the above drawbacks.

β-type titanium alloys, such as Ti–29Nb–13Ta–4.6Zr, Ti–35Nb–5Ta–7Zr and Ti–24Nb–4Zr–8Sn (abbreviated as Ti2448), are attracting increasing research interest due to their advantages of low modulus and the presence of only non-toxic elements [13,18]. For example, β-type Ti2448 exhibits a low modulus of ~42–50 GPa (compared with α+β-type titanium alloys ~100–120 GPa) coupled with high biocompatibility and mechanical properties [11,19–21]. Ti2448 has been successfully manufactured into dense and porous components via both EBM and SLM [5,22]. Ti2448 porous structures with designed porosity of 85% have been produced using SLM. These parts exhibit high relative density (~99.3%), low Young's Modulus (~1 GPa) and high compressive strength (51 MPa) [10]. Ti2448 solid parts obtained via EBM at a preheating temperature of ~200 °C consist of large columnar grains aligned with the build direction and possess high hardness (~2.5 GPa) [22], which is higher than that of SLM-fabricated sample (~2.3 GPa) [5]. This suggests that EBM- and SLM-produced components display significant differences in their microstructure.

However, there have been no reports on comparing the performance of porous β-type titanium alloys structures manufactured by EBM and SLM. Such work could further underpin the understanding of the influence of microstructure and defects produced by these two well-known methods on the resultant mechanical properties. In this study, a 75% porosity structure was made from Ti2448 by using both EBM and SLM. The phases were determined and the melt pool was characterized in terms of size and shape. The number and distribution of defects were analyzed and a mechanism for their formation was proposed. The role of the defects on compressive mechanical strength and fatigue property was also examined.

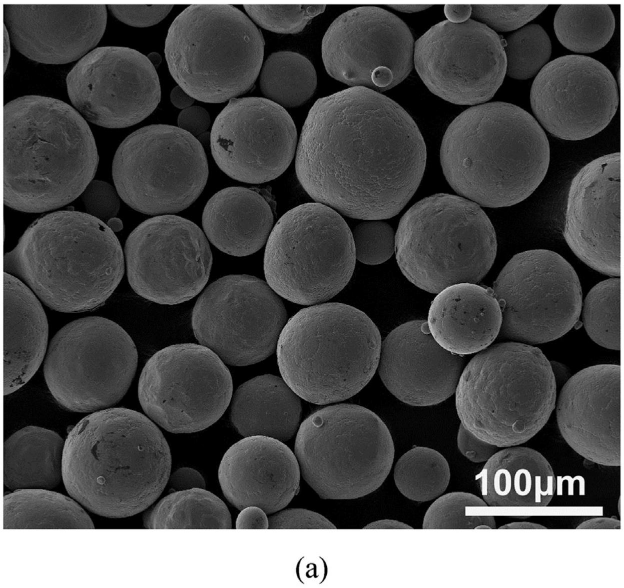
2. Experimental procedures

2.1. Powder material

The powder used was gas atomized in argon from a Ti–24Nb–4Zr–8Sn ingot. The chemical composition of the powder is given in Table 1. The Ti2448 powder was spherical in shape (Fig. 1 (a)), with a nominal particle size distribution between 45 and 106 μm and an average particle size (d_{50}) of 80 μm (Fig. 1 (b)). Powder from the same batch was used for both SLM and EBM.

Table 1
The chemical composition and particle size of Ti2448 powder used for additive manufacturing.

Composition (wt%)					Particle size (μm)		
Ti	Nb	Zr	Sn	O	d_{10}	d_{50}	d_{90}
Bal	23.9	3.90	8.20	0.19	47.2	79.4	130.2



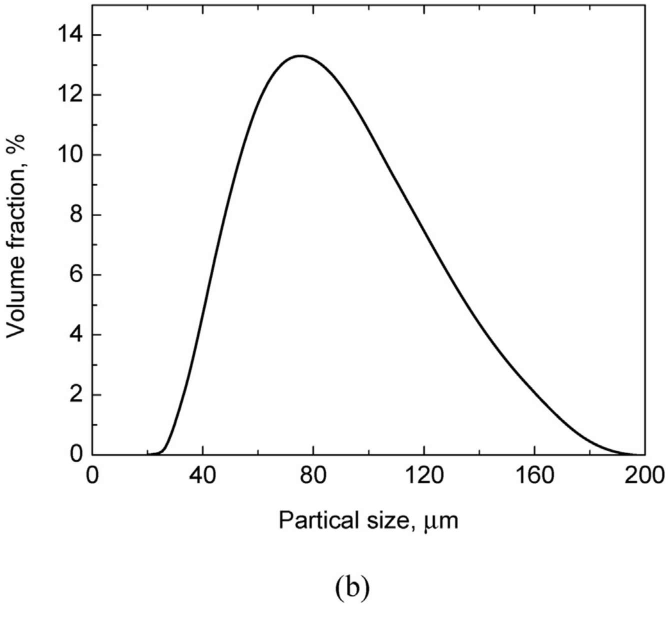


Fig. 1. (a) The morphology and (b) particle size distribution of the as-received Ti–24Nb–4Zr–8Sn powder.

2.2. Electron beam melting process

The EBM samples were made using an Arcam A1 System, with a layer thickness of 70 μm and a processing voltage of 60 kV. The build plate was preheated to 500 °C to avoid smoking during the process. Samples were manufactured directly on a titanium substrate plate, which was maintained at a temperature between 450 and 500 °C by the electron beam. The whole build process was