The influence of processing parameters on strut diameter and internal porosity in Ti6Al4V cellular structure

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THE INFLUENCE OF PROCESSING PARAMETERS ON STRUT DIAMETER AND INTERNAL POROSITY IN Ti6Al4V CELLULAR STRUCTURE

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Abstract

Ti6Al4V cellular structures were fabricated by selective laser melting using a wide range of processing parameters. Optical and scanning electron microscopy were employed to analyze the influence of laser power and scan speed on the strut diameter and the internal porosity. Strut diameter was found to be dependent on the input energy. It increased with increasing the input energy density. As for the internal porosity, at low laser power and high scan speed discontinuity within the struts and defects with entrapped non molten powder particles were observed. While at intermediate laser power and scan speed irregular defects caused by lack of diffusion were formed. At high laser power and low scan speed large pores were about 70µm were formed.

Key Words

Selective laser melting, lattice structure, processing parameters, porosity

Introduction

Porous structures possess unique properties in terms of thermal, electrical and mechanical properties due to their architecture and low density, which makes them desirable in many different applications such as filtering, automotive, aerospace and medical applications[1]. Ti6Al4V lattice structures are widely investigated for medical implant applications since Titanium and its alloys are known for their low density, high strength, corrosion resistance and most important of all is their high biocompatibility[2]. Furthermore, the nature of the lattice structures allow the bone ingrowth within the pores which enhances the implant fixation[3].

Lattice structures are considered a type of porous structures, which are composed of inter-connected solid struts forming a unit cell that is the building unit of a lattice structure[4]. Porous structures are traditionally fabricated using casting methods[5,6], foaming[7] and stack and bond process[7,8]. However, fabricating porous structures with complex geometries with these traditional processes was a difficult task. Hence, introducing the additive laser manufacturing (ALM) technology made it is possible to produce cellular structure with complex architecture[1].

Selective laser melting (SLM) is one of the additive laser manufacturing (ALM) processes. Starting with preparing the STL file with the required design which is cut to slices with predetermined thickness. Afterwards a layer of powder particles spread with defined thickness, the laser beam starts scanning over the powder material based on the CAD model to melt and rapidly solidify to create a consolidated layer. Subsequently, another layer of powder is deposited over the previously solidified layer and same process takes place until the final product is produced[9,10].

Despite the previously mentioned advantages of SLM processing over the conventional ones, using non optimized fabrication conditions in SLM results in a mismatch between the design and fabricated structure, in addition to internal defects that influences the porous structure performance[10]. Previous studies have widely investigated the influence of SLM processing parameters on the porosity level and morphology for bulk structures hence, process maps were developed for the defect formation mechanisms[11-14]. For example, Dilip et al[1]. studied the influence of SLM processing parameters on porosity evolution in an optimized process window of (150W, 750mm/s) and (195W, 1000mm/s), which was selected to give a nearly fully dense part. However, for cellular structures studies focused on the influence of the processing parameters on the mechanical properties and the morphology of fabricated structures[10,15-18]. Sing et al.[19] Investigated the influence of the processing parameters for pure titanium cellular structure on the strut diameter and thickness of powder adhesion. As for strut diameter, decrease in strut diameter was observed at all studied condition when compared to designed model. Regarding the thickness of adhesion powders, it decreases upon increasing the laser input energy. Accordingly, this study aims at deriving valuable correlation between the SLM processing parameters and the morphology of the built cellular structure in terms of the strut size and the internal porosity, which are directly influencing the produced mechanical properties.

Experimental Procedures

Materials and Processing

Gas atomized Ti6Al4V powder supplied by TLS Technik, Germany with a size range of the 20-50 μm was used for building the BCC cellular structures as show in Figure 1. A Concept Laser M2 Cusing SLM system of maximum laser power capability of 400 W, scan speed up to 4000 mm/s was used for fabricating the cellular structure. The fabrication process was performed in Argon atmosphere.

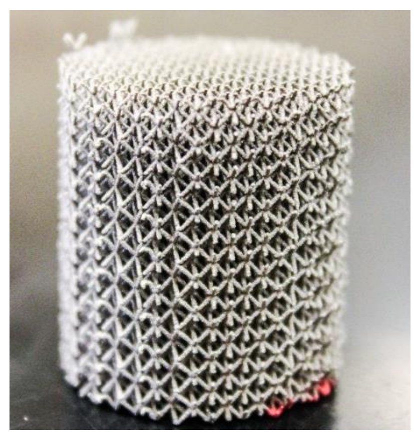


Figure 1. Lattice structure fabricated using SLM

BCC cellular structure composed of connected struts with 200 μm diameter build in the form of cylindrical specimens were fabricated with dimensions of 25x30mm. In order to study the influence of the SLM processing parameters on the strut diameter and internal porosity, a set of lattice structures were built with constant layer thickness of 30 μm using a contour scanning strategy at different scan speeds and laser power that are listed in the next section.

Evaluation of the Fabricated Structure

Before characterization, all lattice structures where cleaned in acetone for 3 minutes to ensure the removal of any dirt or trapped lose powder. Field emission scanning electron microscope (FEG-SEM) Leo Supra 55—Zeiss Inc, with accelerating voltage up to 30 KV was used for investigating the morphology of the lattice struts. As for the strut diameter measurements, lattice structures were sectioned through the x-z direction (z-represents the cylinder height) mounted, ground and polished. Polished samples were examined under optical microscope (Leica DM

IRM) for studying the internal porosity in the lattice structures. Sectioned lattice structures were investigated using optical microscopy, while ImageJ 40 was employed to evaluate the different strut diameters as a function of the SLM processing parameters.

To determine the suitable processing parameters for producing a dense lattice structure with high geometrical accuracy compared to the initial CAD model, a set of structures were built with laser power ranging from 100W to 300W and scan speed ranging 8000 mm/s to 4000 mm/s. All the structures were characterized and only three conditions are presented in this manuscript. The selected conditions represents different levels of input energy density. The lattice structures have been evaluated based on two different aspects, which are the influence of input energy on the strut diameter and the porosity level.

Results and Discussion

Influence of Input Energy on Strut Diameter

Table I. Processing parameters and strut diameter

Laser power (w)	Scan speed (mm/s)	Strut diameter (µm)
100	4000	163
200	2400	220
300	800	267

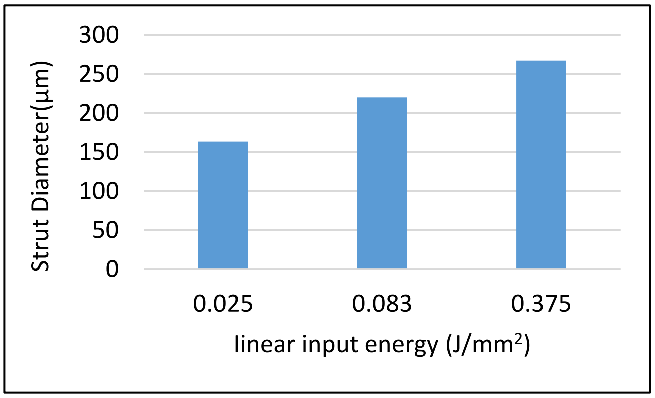
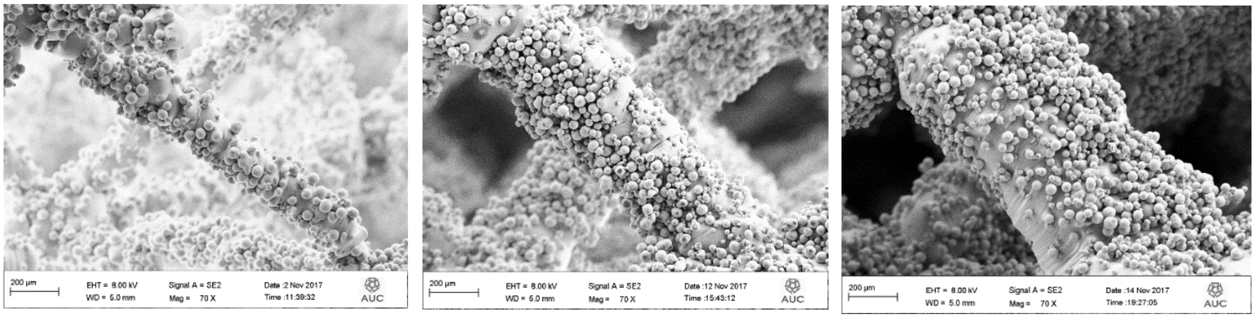


Figure 2. A diagram showing the variation of Strut diameter as a function of increasing linear input energy diameter

The fabricating conditions listed in table I directly influenced the strut diameter of the fabricated lattice structure. As shown in Figure 2, the strut diameter increased with increasing the input energy. This relation is attributed to the fact that inclined struts were built partially on loose powder, which resulted in adhesion of free powder (partially melted powder particles) to the surfaces of the struts. At high input energy condition, the energy transferred to attach powder particles was high enough to result in full melting of the attached powders and hence became part of the fabricated strut[19]. SEM images at the same magnification that are presented in Figure 3 show evidence for the measurements made and displayed in Figure 2.

The Aforementioned Observation agrees with the findings of Mullen et al.[20] In a study that evaluated the influence of laser beam energy and strut orientation on strut diameter of fabricated samples and it was concluded that strut diameter increase with increasing the laser energy and building angle of the strut. The fabrication technique of the inclined struts has a direct influence on the surface roughness and waviness induced to the struts “staircase effect”; this technique contributes in the gap between the actual and designed strut diameter[18].

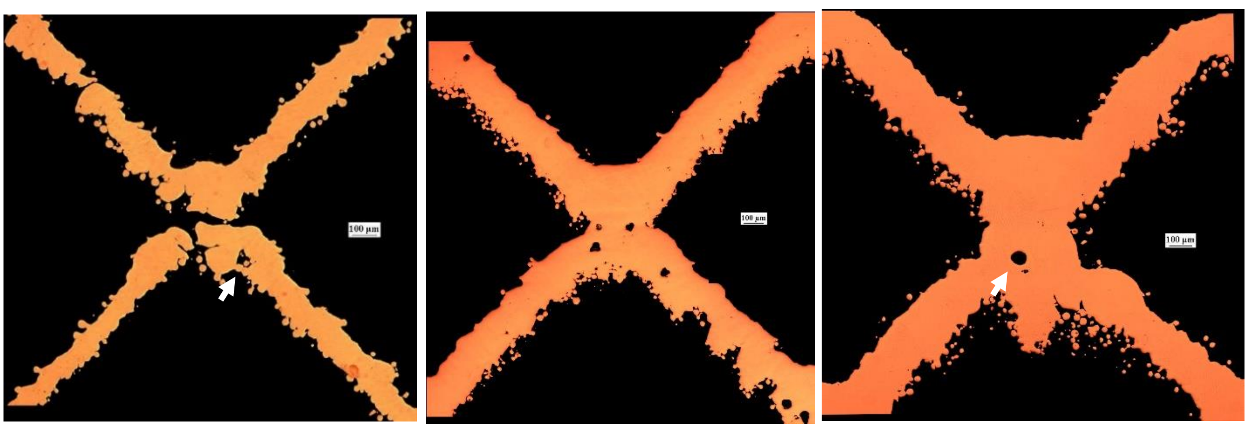


(a) (b (c)

Figure 3. SEM images for struts at different fabrication conditions (a) 100W &4000mm/s (b) 200W & 2400mm/s (c) 300W & 800mm/s

Influence of Input Energy on Internal Porosity

Investigation of the sliced sections along the x-z plane of the struts as a function of the three selected processing parameters is shown in Figure 4. Different zones were formed as a result of using different processing parameters. Those zones depend on the input energy during the SLM process. Accordingly, correlation between the input energy at the selected SLM processing conditions with the developed internal porosity of the lattice can be presented as follows:



(a) (b) (c)

Figure 4. OM micrographs for internal porosity at different conditions (a) 100W &4000mm/s (b)200W & 2400mm/s (c)300W & 800mm/s

Zone I: Low input energy: this zone is created as a result of combining low laser power with high scan speed. Such combinations resulted in the partial melting of the powder, creating an insufficient liquid phase[21].The relatively low associated heat input led to the discontinuity within the strut due to the lack of diffusion between the melt pools. In addition, lack of diffusion defects were also manifested by the enclosed non molten powders, as indicated by the arrow in Figure 4a[12]. Moreover, a balling effect could be spotted in this zone, which is one of the well-known defects generated during SLM processes. This phenomena occurs at high speed conditions, due to poor wettability with the preceding layer leading to spheroidization of the melt-pool[22,23]. This balling effect had an adverse effect on the lattice integrity because it resulted in the detachment of the struts.

Zone II: Intermediate input energy zone: this zone is the resultant of intermediate laser power and scan speed. Irregular defects are formed as shown in Figure 4b due to the lack of diffusion between melt pools[12]. Irregularity in the struts thickness could be observed due to the fabrication technique of the inclined struts, which induces this type of waviness to the strut[18].

Zone III: High input energy zone: this zone was developed due to the combination of high laser power and low scan speed. This zone was associated with high temperatures resulting in sufficient molten material that mitigated the previously formed lack of diffusion defects. Spherical pores were also observed as shown in Figure 4c.Those defect could be attributed to the evaporation of alloying elements at such high input energy gained by the powder[11]. It was observed that those spherical pores are only formed at the node while the struts are free from defects. This could be attributed to the several thermal cycles at the node for being the intersection of four struts.

Conclusion

SLM processing parameters investigated in the current research shows that the input energy density has a significant influence on the strut diameter and porosity morphology within the fabricated struts. Different zones were developed based on changing the input energy. Additionally, it was observed that strut diameter size for Ti6Al4V lattice structure increased with increasing the input energy density.

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