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Selective laser melting of lattice structures: A statistical approach to manufacturability and mechanical behavior

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ABSTRACT

This paper investigates the effect of processing parameters on the dimensional accuracy and mechanical properties of cellular lattice structures fabricated by additive manufacturing, also known as 3D printing. The samples are fabricated by selective laser melting (SLM) using novel titanium-tantalum alloy. The titanium-tantalum alloy has the potential to replace commercially pure titanium and Ti6Al4V as biomedical material. In this study, the unit cell used is specially designed to carry out the analysis using regression method and analysis of variance (ANOVA). Due to the effect of the SLM process parameters, the elastic constant of the cellular lattice structures ranged from 1.36 ± 0.11 to 6.82 ± 0.15 GPa using the same unit cell design. The elastic constant range, while showing the versatility of titanium-tantalum as biomedical material, is rather wide despite using the same lattice structure designed. This shows that there is a need to carefully control the processing parameters during the lattice structures fabrication so as to obtain the desired mechanical properties. Based on the statistical analysis, it is found that the dimensional accuracy and mechanical properties such as elastic constant and yield strength of the cellular lattice structures are most sensitive to laser power as compared to other parameters such as laser scanning speed and powder layer thickness.

1. Introduction

Selective laser melting (SLM) is one of the additive manufacturing (AM) techniques that are capable of fabricating metallic functional parts directly. The SLM process has been detailed in previous works [1–3]. One of the key advantages of SLM is the freedom of designs it provides in manufacturing. Multiple studies have been conducted using this process in manufacturing of parts with complex structures for various applications. This process is especially beneficial for biomedical applications due to their high value [4–6].

For biomedical applications, such as implants, typical metallic materials used in SLM have higher modulus than natural bones. Modulus mismatch can cause an adverse effect called "stress shielding" [7]. Stress shielding induces an undesirable stress distribution at the bone-implant interface, resulting in slower bone healing [7,8] as the bone remodels itself from the lack of stress stimulant. Clinical investigations indicate that the mismatch will result in insufficient load transfer from artificial implants to neighboring bones, resulting in bone resorption and potential loosening of the implant [9]. In order to minimize the adverse effect, cellular lattice structures fabricated by SLM have been studied [10–13]. The design freedom from SLM comes with associated complexity. As SLM is a layer-by-layer AM process, the struts formations in different directions undergo different mechanisms. For the horizontal struts, they are formed by single or multiple continuous melt tracks, depending on the strut dimensions. For the vertical struts, they are formed by direct stacking of single or multiple melt pools across multiple layers. For struts inclined at an angle, for example, diagonal struts, they are formed by stacking of single or multiple melt pools across multiple layers that are offset from each other. The offset depends on the incline angle of the struts.

Exploring the design space using experiments can be challenging as there is a large number of parameters, such as laser power, laser scanning speed, hatch spacing and layer thickness, which influence the process and thus the final quality of the part [14–17]. Zhang *et al.* studied the effect of hatch spacing on pore characteristics of Ti6Al4V structures fabricated using SLM. Pores are formed by varying hatch spacing of the laser scans, instead of specific designs using CAD. The laser spot size used is 200 µm, hence, it is found that a hatch spacing of distance greater than the spot size is necessary for pores formation. Partially melted pow-

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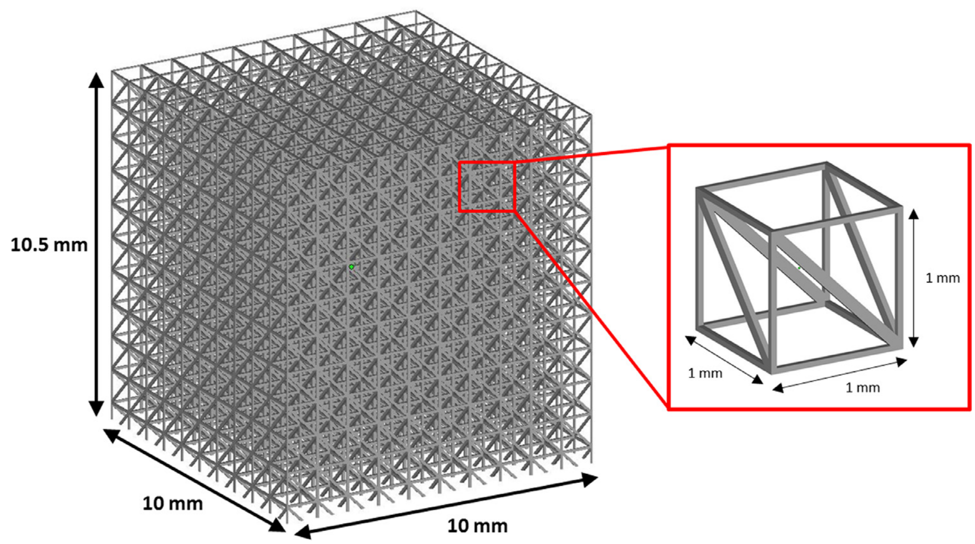

Fig. 1. CAD file of cellular lattice structures.

der particles are also observed to adhere onto the strut surfaces. Due to the accumulation effect of the biggest powder, it is advised that the pore diameter should be three times greater than the biggest powder particles for forming interconnected pores [18]. In the same study, it is also concluded that the powder particle size has an important influence on the formation of porosity and laser spot size directly determines the strut width. Qiu *et al.* [19] investigated the influence of laser power and scanning speed on strut size, morphology and surface structures. It is found that higher laser powers lead to formation of thicker struts with larger deviation from the designed strut diameters. Higher laser power also leads to an increased powder adhesion on the struts. Similar results are concluded by Sing *et al.* using statistical analysis that laser power and scanning speed has effect on powder adhesion on the strut surfaces [1]. However, the scanning speed only affect the strut diameter at lower end of the scanning speeds [19]. All these results coincide with study by Tsopanos *et al.* which states that laser fabricated the strut diameter is dependent on the energy applied on the powder, which is related to the laser power [20].

Statistical modeling allows an inexpensive method in analyzing the key factors in influencing the parts quality and mechanical properties. The use of design of experiments (DOE) techniques such as regression analysis and statistical analysis using the analysis of variance (ANOVA), has shown to be useful approaches to study the effect of many parameters in material processing applications [21]. Despite the studies conducted, there is limited information on the effect of processing parameters of SLM on the quality and mechanical properties of cellular lattice structures. This study focuses on the effect of processing parameters on the forming mechanisms of the struts of cellular lattice structures, their resulting dimensions and properties.

2. Methods and materials

2.1. Design of lattice structures

The cellular lattice structures used in this study are specially designed in order to study the effect of processing parameters on the quality and mechanical properties of these structures. The unit cell designed consist of vertical, horizontal and diagonal square struts of 0.080 mm sides which corresponds to the spot size of the laser in the SLM 250 HL machine (SLM Solutions Group AG). Vertical, horizontal and diagonal struts are chosen to investigate the different building direction capabilities of SLM.

The dimensions of the repeating unit cell are 1 mm by 1 mm by 1 mm. The generated CAD diagram is shown in Fig. 1. The overall dimensions of the lattice structures are 10 mm by 10 mm by 10.5 mm, with allowance given in the height to allow for erosion of materials from electrical discharge wire cutting of the samples from the substrate plate.

Table 1
Factors for regression analysis.

Factor		Values		
		(−1)	(0)	(1)
P	Laser power (W)	120	240	360
S	Laser scanning speed (mm/s)	400	800	1200
L	Layer thickness (mm)	0.030	0.050	0.100

2.2. Design of experiment for regression analysis and analysis of variance

Regression analysis is used to determine the value of coefficients of the function that cause the function to best fit a set of observed data [22]. There are mainly two types of regression techniques, namely linear and non-linear regression. This method is employed to develop empirical model for predicting output parameters under a set of controlled experimental factors. Regression analysis optimization process involves three major steps [23]:

1. Performing the statistically designed experiments
2. Estimating the coefficients in a mathematical model
3. Predicting the response and examining the adequacy of the model

The significant variables, laser power, laser scanning speed and layer thickness, were chosen as the critical variables designated as *P, S* and *L*, respectively. The factors and their three levels for the 3^3 factorial design are listed in Table 1.

In order to evaluate the SLM key factors and their effects on the strut dimensions, porosity and mechanical properties of cellular lattice structures, a polynomial equation [21,24] is expressed as follows:

$$y = a_0 + \sum a_i x_i + \sum a_{ii} x_i^2 + \sum \sum_{i<j} a_{ij} x_i x_j + \varepsilon \quad (1)$$

where y is the response or dependent variable investigated (strut dimensions, porosity, yield strength and elastic modulus), a_i is a correction constant coefficient, a_i, a_{ii} and a_{ij} are coefficients for linear, quadratic and interaction effect, x_i and x_j is the independent variables (laser power, scanning speed and layer thickness) and ε is the random error. The polynomial equation assumes that third order interactions of the independent variables are insignificant. Analysis of Variance (ANOVA)