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Evaluations of Co-Cr-Mo Meta-Biomaterial Manufactured by Selective Laser Melting for Orthopaedic Application

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Abstract

Meta-biomaterial with rationally design geometrical features provides an exciting opportunity to reduce stress shielding effect and enhance biological fixation as vital criteria for longer durability load-bearing implants. Recently, selective laser melting (SLM), an additive manufacturing has shown significant advantages to produce complex shape which component's dimensions are close to final dimensions with high degree of interconnected structure. Nonetheless, the available data on achievable accuracy of parts with different geometries from this manufacturing process is scarce. In this study, meta-biomaterials with two different unit cells types made of cobalt chrome molybdenum (Co-Cr-Mo) namely square and diamond are designed with varied unit cell length, L_{cell} of 1.5 mm and 2.5 mm while strut size, Φ_S of 0.4 mm and 0.6 mm then fabricated by SLM. The effects of unit cell geometries on the manufacturability and density were investigated. The manufacturability accuracy has a good geometric agreement between fabricated samples and original computer aid designed models (CAD). The optical microscope images reveal the partially melted metal particles are bonded to the strut surface. The structures with bigger strut size have higher density due to denser struts.

Keywords: Load-bearing ; meta-biomaterials ; Co-Cr-Mo ; selective laser melting (SLM) ; manufacturability

1. Introduction

Meta-material best known as a newly way assembling unit cell structures to achieve combination effects of material properties and structural behavior[1]. The structure can offer high performance features such as high yield strength accompanied by relatively lightweight[2], low density[3], acoustic insulation[4], good energy absorption and thermal transfer[5] make it suitable for high technology values of aerospace, medical and engineering component[6]. Studies on design and manufacturing of the meta-materials become increasingly important due to attractiveness of ultra-stiff and ultra-strong with extraordinary properties for any selected applications[7].

For orthopaedic implants, biocompatible Co-Cr-Mo alloys are one of routinely used metallic biomaterial due to excellent fracture toughness, wear and corrosion resistance[8]. Despite of the excellent properties, Co-Cr-Mo exhibit high elastic modulus (~210 GPa) where much stiffer than human bone that is ranging from 1-30 GPa[9]. This mismatch stiffness will changed the mechanical stimulus in bone adjacent to the implant placement where is

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known as stress-shielding effect[10,11]. The worst scenario of stress-shielding generates a loss of bone density or bone resorption which leads to early revision surgery after implantation[12]. Efficient load transfer is important in load-bearing application in order to provide functionality and maintain mobility of the patients.

Previous research studies determined the Co-Cr-Mo cellular structures exhibit elastic moduli comparable to human bone where it is significant to reduce number of stress-shielding cases[13-17]. Recent advance in additive manufacturing have enabled fabrication of complex three-dimensional (3D) structures with high precision and controllability at microscale level[18]. In contrast with conventional methods that can produce simple geometries and limited freeform shape whereas subsequently lack advance functionality to meet more complex requirements for an application.

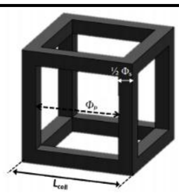
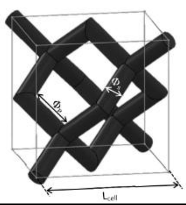
This paper is aims to evaluate the performance of Co-Cr-Mo meta-biomaterial namely square and diamond with varied unit cell length, L_{cell} and strut size, Φs. The effects of varied geometrical parameters on manufacturability accuracy and density were investigated.

2. Experiment methods

2.1. Preparation and design of meta-biomaterials

Meta-biomaterials were made from Co-Cr-Mo alloy powder with 90% powder particle size is in range of 22 µm. From scanning electron microscopic analysis, the powders have a narrow particle size distribution and nearly spherical shape with smooth surfaces which lead to good flowability. The CAD models of square and diamond unit cells were generated through SolidWorks 2013. The details geometries of the meta-biomaterials is illustrates in Table 1. Each unit cells was built into rectangular parts with dimension approximately 12 x 12 x 15 mm^3.

Table 1. Geometrical parameters of meta-biomaterials.

Unit cell		Unit cell length, $L_{cell,}$ mm	Strut size, $\Phi_{S,}$ mm	Pore size, $\Phi_{P,}$ mm	Volume porosity, %
Square		1.5	0.4	1.1	79.8
			0.6	0.9	60.9
		2.5	0.4	2.1	91.0
			0.6	1.9	81.7
Diamond		1.5	0.4	1.1	70.7
			0.6	1.0	44.8
		2.5	0.4	1.9	75.6
			0.6	1.8	86.1

2.2. The process of selective laser melting

The SLM manufacturing process was carried out using SLM® 125HL machine. All the process occurs in an argon atmosphere with purity 5.0%. The SLM machine uses a 400 W Ytterbium fibre laser with an operational beam diameter focus to 80 µm at set point of 150 °C. The process parameters in this study were as follows; the laser power was 300 W; the layer thickness was 30 µm; the scan spacing was 0.12 mm; the scanning speed was 700 mm/s. All meta-biomaterials were built by SLM process on a stainless steel base plate and then detached from the base plate using wire Electrical Discharge Machining (wire-EDM).

2.3. Measurements and characterizations of meta-biomaterials

An optical microscope (Dino-lite Digital Microscope) was used to investigate and analyse the strut sizes of as-built meta-biomaterials. For every optical microscope image, ten dimensional values were measured at random point and the average values were calculated. The densities of the meta-biomaterials were measured according to Archimedes' principle. The relative density was calculated by the ratio of the fabricated meta-biomaterials to the density of fully dense Co-Cr-Mo alloys taken here as 8.29 g/cm^3 according to standard material specification.

3. Results and discussion

3.1. Manufacturability of Co-Cr-Mo meta-biomaterials by SLM

Fig. 1 shows the samples after fabrication process where the samples were built on the stainless steel plate. From the figures, the support angle for square unit cell type is 45° to reduce the overhang on the sample. The optical microscope images of as-built meta-biomaterials are shown in fig. 2 where it is clearly seen that struts of meta-biomaterial are well fabricated by SLM process where the struts are solid and interconnected eventhough the surfaces are rough. The rough surface is due to existence of partially melted powder that attached to the strut surfaces. The factors of bonded particles on strut have been discussed elsewhere[2]. The strut sizes of meta-biomaterials were analysed and summarised in Table 2.

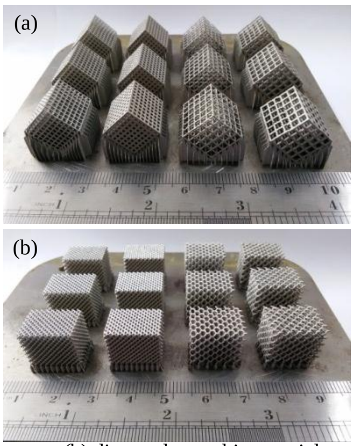


Fig. 1. (a) square; (b) diamond meta-biomaterials on base plate.

Table 2. Strut sizes of meta-biomaterials measured using optical microscope.

Unit cell type	Unit cell length, L_{cell}, mm	Designed strut size Φ_S, mm	Measured strut size, Φ_S, mm
Square	1.5	0.40	0.41
		0.60	0.61
	2.5	0.40	0.41
		0.60	0.61
Diamond	1.5	0.40	0.39
		0.60	0.60
	2.5	0.40	0.40
		0.60	0.60

From the table, the partially melted powder particles will increase of strut size measurement for square unit cell type. The self-supported feature that exhibit in diamond unit cell type due to inclination angle between the two adjacent layers can capability to support the fabrication of next layer. Therefore, the diamond type results the good geometric agreement with CAD models. However, the smaller unit cell size of diamond type results inaccuracy due to loss connectivity between adjacent cell layers or strut too thin to be produced by SLM process.

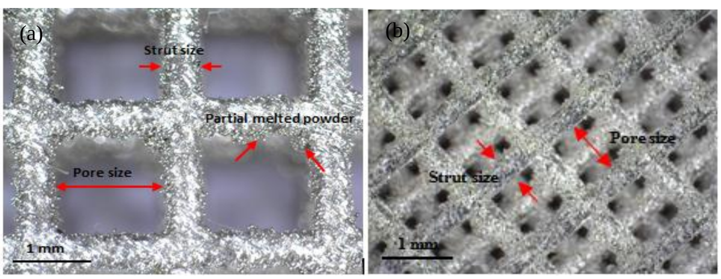


Fig. 2. Optical microscope images (a) square; (b) diamond shows partially melted powder attached on the strut surface.

3.2. Dimensional accuracy of Co-Cr-Mo meta-biomaterials

Dimensional measurements particularly for height of samples were measured using Vernier calliper where ten randomly measured and the average was calculated. Table 3 shows the obtained dimensional measurement. For additional, the average heights of produced samples are measurement and illustrated in fig. 3 where the designed heights of all meta-materials are approximately ~15 mm.

Table 3. Dimensional measurement of Co-Cr-Mo meta-biomaterials.

Sample	Designed dimension, mm	Measured using digital Vernier calliper, mm
S_L1.5_T0.4(1)	12.4x12.4x15.4	12.6x12.6x15.3
S_L1.5_T0.6(2)	12.6x12.6x15.6	12.7x12.8x15.4
S_L2.5_T0.4(3)	12.9x12.9x15.4	13.2x13.2x15.5
S_L2.5_T0.6(4)	13.1x13.1x15.6	13.3x13.3x15.6
D_L1.5_T0.4(5)	12.0x12.0x15.0	12.1x12.1x15.1
D_L1.5_T0.6(6)	12.0x12.0x15.0	12.1x12.1x15.0
D_L2.5_T0.4(7)	12.5x12.5x15.0	12.7x12.6x15.0
D_L2.5_T0.6(8)	12.5x12.5x15.0	12.6x12.6x15.0

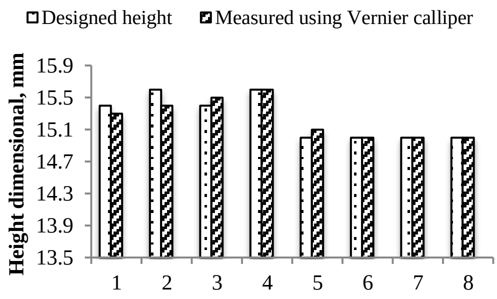


Fig. 3. Dimensional accuracy of height of samples.

3.3. Effect of volume porosity on density of Co-Cr-Mo meta-biomaterials

The densities and relative densities of the square and diamond unit cell type meta-materials are shown in Table 4 while the fig. 4 illustrated the density and relative density within the volume porosity of meta-biomaterials respectively. From the graph, the densities for smaller struts are lower than densities of bigger struts.

Table 4. Density and relative density of Co-Cr-Mo meta-biomaterials.

Sample	Volume porosity, %	Measured density, g/cm^3	Relative density, %
S_L1.5_T0.4	79.8	8.09	97.57
S_L1.5_T0.6	60.9	7.67	92.49
S_L2.5_T0.4	91.0	7.75	93.48
S_L2.5_T0.6	81.7	7.99	96.37
D_L1.5_T0.4	70.7	7.02	84.68
D_L1.5_T0.6	44.8	7.69	92.70
D_L2.5_T0.4	75.6	8.07	97.29
D_L2.5_T0.6	86.1	7.67	92.57
Full dense	-	8.23	99.29

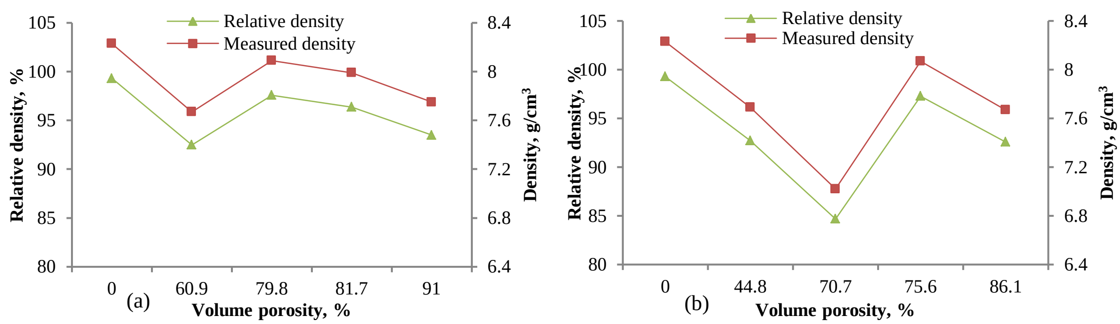


Fig. 4. Relative density and density of (a) square; (b) diamond unit cell with variation of volume porosity.

4. Conclusion

This study determines the dimensional accuracy and density of SLM manufactured Co-Cr-Mo meta-biomaterials by evaluating the manufacturability of unit cell type with variations of unit cell length and strut size. The meta-biomaterials were designed by repeating unit cell type namely square and diamond which occupy cubic and spherical strut core respectively. The SLM-manufactured Co-Cr-Mo meta-biomaterials possess good geometrical agreement with original CAD models. However, optical microscope results reveal that many partially melted powder particles were attached to the strut surface especially for square type which resulting higher strut size and smaller pore size from original CAD models. The manufacturability accuracy of strut size shows the diamond unit cell type has better results compared to square unit cell due to capability of self-supported featured and this can reduce overhang effect unless for smaller strut size where the strut is too thin to be manufactured. The diamond unit cell type results the lower relative density which is ranging from 84.86% to 97.29% while relative densities for square unit cell is ranging from 92.49 % to 97.57%. The lower densities of meta-materials are shown for bigger unit cell length with smaller strut size due to less dense of meta-material features for both unit cell types.

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