Manufacturability and mechanical testing considerations of metallic scaffolds fabricated using selective laser melting: a review

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Abstract

Selective laser melting (SLM) allows the direct fabrication of metal functional parts with complex shapes from digital models. In particular, metallic scaffolds with lattice structures and controlled porosity for orthopedic applications have recently gained interest, exploiting SLM manufacturing technique. In this review, the current developments in SLM for metallic scaffolds fabrication has been highlighted. The paper focuses on the manufacturability of metallic scaffolds by SLM and their mechanical properties. This paper will serve as a guidance for implementing SLM for manufacturing medical devices.

Introduction

Additive manufacturing (AM) includes a group of processes to fabricate objects from data on a three-dimensional (3D) model, usually layer by layer, as opposed to conventional subtractive manufacturing methodologies.[1,2] In recent years, there has been numerous studies applying AM techniques in tissue engineering,[3-6] mainly making use of biodegradable polymeric materials. With the advancement of AM technologies, there are now techniques for the direct fabrication of functional metallic parts, and many works have been extended to the study of metallic scaffolds for biomedical applications, that combine the biological functions and load bearing functions. Metallic scaffolds retain their shape, strength and biological integrity during the bone regeneration process; hence, they can be used as permanent scaffolds for hard tissue repair in a load-bearing areas.[7]

Conventional manufacturing methods for metallic scaffolds also exist including space-holder method,[8] polymeric sponge replication,[9] decomposition of foaming agents,[10-12] fiber meshes and fiber bonding.[13] However, these techniques offer limited control on pore size, pore geometry and porosity. On the contrary, AM techniques, such as electron beam melting (EBM) and selective laser melting (SLM), allow a better control of pore size, pore geometry and porosity.

Particularly, based on ISO/ASTM52900 - 15, SLM is classified as a powder bed fusion AM technology.[14] Being an AM technique, one of the key advantages of SLM is that it does not have the typical design constraints that conventional manufacturing techniques have, allowing complex geometries to be built. In addition, no tooling or moulds are required for SLM. Therefore, it is able to provide greater freedom of design to product developers and to significantly lower the customization cost.[1,15] SLM is considered of being able to produce structures of complex freeform geometry and is showing great potential in manufacturing cellular lattice structures with fine features at high resolution.[16]

Metallic scaffolds offer various advantages, such as biocompatibility, immediate partial weight-bearing, support of bone ingrowth into the pores and osteo-synthesis, and long-term stability, together with biocompatibility and bone in-growth ability into the open pores. Additionally, the risk of late fractures due to scaffold instability is almost negligible as long as the bone-scaffold interface is well incorporated with new formed bone.[17] However, metallic scaffolds are not biodegradable and therefore cannot be replaced by newly formed bone. The open porous structures should have sufficient pore size for bone in-growth and nutrient supply. Furthermore, there are still other considerations involved in the fabrication of these scaffolds such as the manufacturability of the designs and the dimensions accuracy. Although SLM can theoretically fabricate metal parts with any shape, the manufacturing quality can differ as the design and processing parameters change.[18] SLM allows full control over both the geometrical and mechanical properties of the scaffolds, which are key features affecting *in vivo* and *in vitro* performance.[19] As stated in the draft guidance on Technical Considerations for Additive Manufactured Devices by Food and Drug Administration (FDA), the major considerations in AM devices are the design, manufacturing process and device testing.

In this paper, the current state of understanding and development of SLM manufacturing process is presented with emphasis on metallic scaffolds. The focus will be on the manufacturability of the porous structures of metallic scaffolds and their mechanical properties.

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Selective laser melting

SLM is a powder bed fusion process that uses fiber laser as an energy source to melt and fuse selective regions of powder according to computer aided design (CAD) data.[20-22] When the selective melting of one layer is completed, the building platform is lowered by a predetermined thickness (typically between 20 to 100 μm) and the next layer of powder is deposited on the platform. This process is then repeated with successive layers of powder until the required part is completely built by fusion of the layers.[1,23,24] At the end of the process, the unmelted powder can be collected, sieved and recycled for the next process. A schematic representation of the SLM process is shown in Figure 1.

Manufacturability considerations for metallic scaffolds using selective laser melting

The manufacturability of metallic scaffolds using SLM depends on the design characteristics of the final scaffolds such as strut dimensions and unit cell shape. There is also the need to consider an appropriate unit cell size as overhanging struts in the cells can lead to deformation. Even though sacrificial support structures can be added to support the overhanging structures, thus preventing deformation, they are difficult to be removed from the interior of complex cellular lattice structures.[16] This adds considerable constraints on manufacturing versatility. A schematic representation of overhanging struts and support structures in a complex cellular lattice structure is shown in Figure 2.

Furthermore, the manufacturability is also dependent on the SLM parameters such as laser spot size, laser power, laser scanning speed, hatch spacing and layer thickness.[18] SLM uses metal powder as feedstock for the process and they are typically spherical in shape to provide good flowability during deposition of the powder layers.[20] The powder particle size used also has an effect on the manufacturability of the structures as well. A scanning electron microscopy (SEM) image of typical SLM powder is shown in Figure 3.

A sample of metallic scaffold fabricated using SLM is shown in Figure 4. Zhang *et al.* studied the effect of hatch spacing, *i.e.* the spacing between parallel laser scans, on the pore characteristics of Ti6Al4V structures fabricated using SLM.[25] In that work, pores were formed by varying the hatch spacing of the laser scans, instead of varying CAD designs. The laser spot size used was 200 μm, hence, it was found that a hatch spacing of distance greater than the spot size was necessary for pores formation. Partially melted powder particles were also observed to adhere on the strut surfaces. Due to the accumulation effect of the biggest powder, it was suggested that the pore diameter should be three times larger than the highest sized powder particles for forming interconnected pores.[25] 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.[25] Sing *et al.* evidenced that laser power and scanning speed had an effect on powder adhesion on the strut surfaces.[26] Similarly, Qiu *et al.* investigated the influence of laser power and scanning speed on strut size, morphology and surface structures.[27] The application of a laser power of 400 W led to the formation of thicker struts with larger deviation from the designed strut diameters and to increased powder adhesion on the struts compared to the use of a laser power of 150 W. However, the scanning speed only affected the strut diameter at low values of the scanning speeds (below 3000 mm/s).[27] All these results were in agreement with the study by Tsopanos *et al.* on the influence of the strut size on the energy applied to the powder, which depends on the laser power;[28] higher energy applied to the powder layer led to thicker struts. The SLM produced lattice scaffolds have usually shown some discrepancies with respect to the CAD designed structures, due to the following reasons (Figure 5): i) an inadequately chosen beam offset does not compensate for the laser spot size used, and hence, the melt pool formed during SLM differs from the desired cross section; ii) a staircase effect, due to layer-by-layer fabrication, causes geometrical differences in the designed and produced struts; iii) loose powder particles are likely to stick to the surface of the parts, which leads to waviness and dimensional inaccuracy.[29] Wang *et al.* concluded that powder adhesion is an inevitable problem in SLM process, especially in the case of overhanging structures affecting the manufacturability of metallic scaffolds by SLM.[18] However, powder adhesion can be minimized by optimizing design and process control.[18] Yan *et al.* also attributed powder adhesion to balling phenomenon which gives rise to beads mainly on laser melted surfaces perpendicular to the building direction.[16] However, Abele *et al*. concluded that building orientation has no significant effect on the manufacturability of lattice struc-

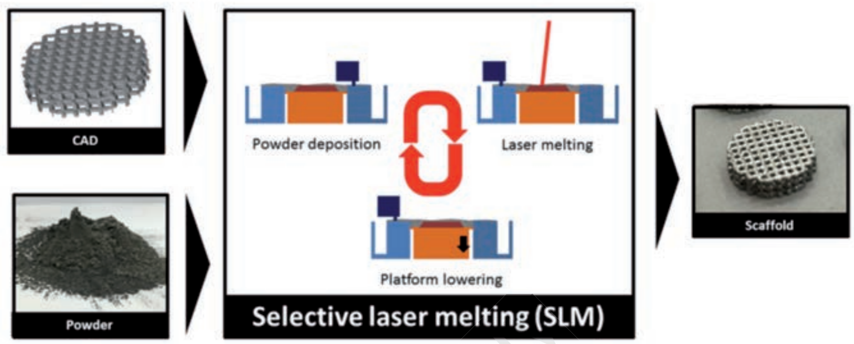

Figure 1. Schematic representation of selective laser melting process.

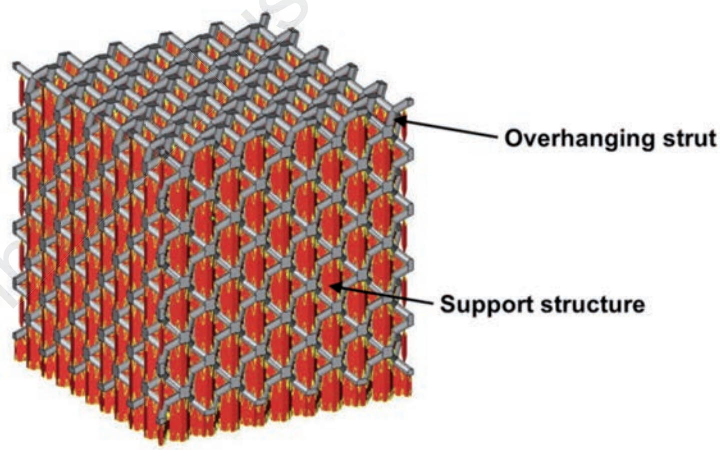

Figure 2. Overhanging struts and support structures for metallic scaffolds.

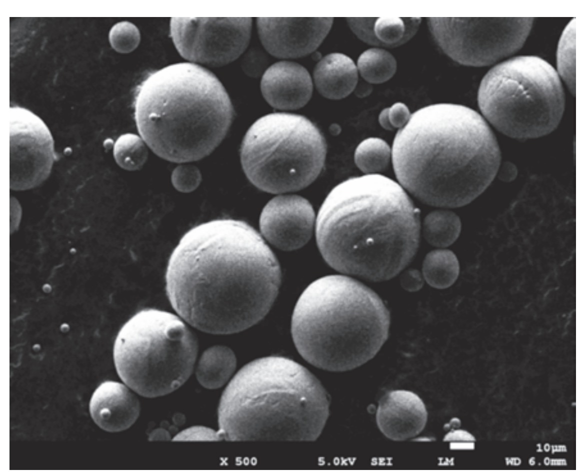

Figure 3. Morphology of powder used in selective laser melting.

tures by SLM,[30] which implies that powder adhesions have no significant effect on the short term mechanical properties. However, powder adhesion can act as stress concentrators, affecting fatigue strength of the porous structures. Furthermore, since powders are loosely bonded to the struts, they can be easily released into the biological environment, causing inflammation.[31] A study of cobalt chromium molybdenum (CoCrMo) based super alloy by Hazlehurst *et al.* has also concluded that structural variation and heterogeneities can have detrimental effect on the stiffness of scaffolds manufactured using SLM.[32] Jet blasting or post-SLM sintering of the structures can lead to localized removal of these powder adhesion, with no effect on the macro-properties of the overall pore or strut network.[33] In order to fabricate lattice structures with precise dimensions, it is important to select appropriate processing conditions or to account for the oversizing of the struts compared to designed diameters.

Mechanical testing of metallic scaffolds fabricated using selective laser melting

The mechanical properties of cellular lattice structures are dependent on their morphological features such as the unit cell, pore size and porosity[34] and are also affected by the processing parameters and powder particle size distribution. These variables affect the porosity of the structures, which based on Gibson-Ashby model, have an influence on their mechanical properties.[26] The type of material used to fabricate the cellular lattice structures is also fundamental in affecting the mechanical properties.[35] Cube or cylindrical samples are usually fabricated for mechanical testing based on ASTM E9 or ISO 13314:2011.[26] Samples of test coupons of lattice structures fabricated using SLM are shown in Figure 6.

Virtual finite element testing

Ahmadi *et al.* studied the analytical solutions and closed-form relations for predicting elastic modulus, Poison's ratio, critical buckling load and yield stress of cellular lattice structures.[34] Finite element (FE) model made up of 14 repeating unit cells could be used to accurately predict the mechanical behaviors of cellular lattice structures made up of any number of repeating unit cells. Smith *et al.* also used FE model to predict the compressive response of 316 L stainless steel lattice structures and found the results in agreement with the experimental values for the SLM produced structures despite using a different unit cell with different design.[36] The predicted value for Young's modulus of the lattice structures ranged from 13 to 227.8 MPa with ranging porosities while the actual experimental values ranged from 10.6 to 207.5 MPa with corresponding porosities. The large range of Young's modulus was due to the varying porosities of the structures. However, a study done by Bültmann *et al.* concluded that there is no scalability of mechanical properties on the struts produced by SLM.[37] Even though FE models are more accurate than mathematical models in predicting the mechanical properties, a disadvantage of FE modeling is the need to develop specific FE models for each defined porous structure which requires specific computation tools.[38] For small apparent density values (less than 0.05), it was found that mathematical models are in good agreement with experimental results, however, for large apparent density values (more than 0.15), the results from the mathematical models deviated significantly from actual experiments.[34] Additionally, Ushijima *et al.* concluded that mathematical models are close to FE models and experimental results when the aspect ratio (*i.e.* the ratio of diameter to length) is relatively small (less than 0.1), while FE models can be used for a wide range of aspect ratios.[39] To summarize, existing FE modelling technique can be used to accurately predict the mechanical properties of SLM produced structures, provided that the whole structure is simulated by the FE model instead of simulating partial

Table 1. Finite element testing of selective laser melting metallic scaffolds.

Material	Mechanical property	Test description	Key findings	Reference
Ti6Al4V	Compression	The struts of the cellular structure were discretized using Timoshenko beam elements, *i.e.* a 2-node linear integration element (type B31), to capture the shear effects that cannot be captured using Euler-Bernoulli beam elements	For small apparent density values (less than 0.05), the mechanical properties obtained using mathematical and numerical solutions (by FE models) were in agreement with each other and with experimental measures	34
316L stainless steel	Compression	Two methods were used to model the lattice structures. The first used 8-node continuum (3D brick) elements to accurately capture both the unit cell geometry and the stress–strain distribution within the struts. The second method used simpler 2-node beam elements to represent the struts in the unit cell.	This study has shown that the quasi-static response of both the unit cell based structures could be accurately described using finite element modelling with both 3D continuum and beam element types; Modelling of large lattice structures was not feasible as the number of elements became extremely large; It was difficult to accurately measure the material properties/ effective strut diameter of individual struts within a lattice structure	36
Ti6Al4V	Compression	The structures are made of four different types of unit cells. The struts are discretized using a number of Timoshenko beam elements.	Comparison between the results of FE models and mathematical models showed that for slender struts the mechanical properties predicted by FE models approached those predicted by mathematical models; FE models are more accurate than mathematical models in predicting the mechanical properties; The structural irregularities that are caused by manufacturing techniques significantly influenced the mechanical properties of porous scaffolds and should therefore be implemented in FE models	38

Table 2. Mechanical properties and testing conditions of selective laser melting metallic scaffolds.

Material	Mechanical property	Test description	Key findings	Reference
Ti6Al4V	Compression	Uniaxial load: tested using a MTS servo-hydraulic test rig with a maximal load capacity of ±15 kN	Samples bore higher maximum stresses before a steep drop occurred at strains of about 5% which was attributed to failure of struts along an entire plane of the cube and was deeper in case of the as-built samples revealing an inferior ductility as compared to heat treated samples; After this collapse, both groups of samples bore load again with higher maximum stresses present in the heat treated samples	40
Ti6Al4V	Tensile	Samples bore higher maximum stresses. Uniaxial load: tested using a MTS servo-hydraulic test rig with a maximal load capacity of ±15 kN	The annealed samples were able to bear higher maximum stresses already at early stages of deformation; The higher ductility of the heat treated condition enabled the struts to align along the loading axis, which eventually improved their load carrying capacity.	40
Ti6Al4V	Fatigue	Cyclic tests: force control was used, applying a peak load of 25% of the maximum load reached by the as-built specimens under monotonic tensile and bending load, respectively	Heat treated samples showed a significantly higher fatigue life; The shortening of the samples (in compressive experiments) was related to strain accumulation and a reduction of stiffness due to crack initiation and growth within the struts.	40
Ti6Al4V	Bending	Four-point-bending: rolls of 16 mm diameter were installed with distances to each other of 35 mm in case of the two upper and of 70 mm in case of the two lower rolls. This setup was mounted to a Bose testing system capable of ±15 kN	Higher ductility was present after annealing; There were more intact struts in the heat treated sample, which are responsible for maintaining the stiffness to a higher level; The heat treated specimens featured a significantly higher fatigue life under cyclic bending load	40
Ti6Al4V	Compression	Tested under compression in accordance with the ISO standard for mechanical testing of porous metallic materials, ISO (13314:2011) Static test machine (Instron 5985, 100kN load cell) under a constant deformation rate of 1.8 mm/min.	The tests were continued until specimens experienced 80% strain. As the number of unit cells used in x-, y-, and z-directions increased from 5 to 20, the cellular structure exhibited a stiffer response; Comparison between the mathematical, numerical (FE models), and experimental results showed that for small values of the apparent density (less than 0.05), all methods yielded very similar results. As the apparent density increased, Young's moduli estimated using the FE model accurately matched the experimental results even for large apparent density values; For density values as low as 0.04, yielding occurred far before buckling for most cellular structures of practical relevance	34
Ti6Al4V	Compression	Mechanical testing machine (SHIMADZU, Japan) applying a 100 KN load cell at a strain rate of 10-3 s-1.	Test with different scan line spacing performed for scan line spacing from 200 µm to 700 µm The fabricated samples with different scan line spacing showed the yield strength in the range of 467–862 MPa and the Young's modulus in the range of 16–85 GPa; The major failure mechanism of the porous structure was the adiabatic shear band (ASB) fracture and there was no significant influence The porous Ti6Al4V samples deformed as a bulk material. The samples fabricated with different scan line spacing had different pore sizes and different porosities but they had the same thin dense walls in the structure. The results showed the brittleness of the porous Ti6Al4V implants due to the dense walls rather than the presence of porosity; In general Ti6Al4V alloy was a ductile material and SLM processed Ti6Al4V also remained ductile up to failure	25

structure or single strut. Key findings from FE testing of the metallic scaffolds fabricated using SLM are summarized in Table 1.

Compressive mechanical testing

Brenne *et al.* studied the compressive deformation behavior of Ti6Al4V cellular lattice structures fabricated using SLM.[40] They showed that samples heat treated at 1050 °C for 2 hours under vacuum with subsequent furnace cooling had significantly higher fatigue life under cyclic bending load as compared to as-built samples.[40] Tsopanos *et al.* studied the compressive behavior of stainless steel micro-lattice structures and concluded that low laser power (70 W compared to 100 and 120 W) produced structures with low yield, ultimate tensile strength and elongation, which is attributed to a significant high number of unmelted powder.[28] Wauthle *et al.* studied the effects of build orientation on the mechanical properties of Ti6Al4V lattice structures with diamond unit cells.[19] A schematic representation showing the build orientations of the lattice structures is shown in Figure 7. Structures build diagonally showed inferior mechanical properties compared to the horizontal and vertically orientated samples which mechanical behavior was nearly identical.[19]

This implies that large horizontal struts should be avoided unless they can be supported with other struts as they cannot be fabricated successfully without support structures. These results are in agreement with findings by Abele *et al.*[30] Amin Yavari *et al.* studied the fatigue behavior of Ti6Al4V porous lattice fabricated by SLM.[41] The static mechanical properties of the porous structures were within the reported range of mechanical properties of bone, however, the normalized endurance limits (0.15 to 0.20) with respect to the yield stress of the tested structures were lower than some other porous structures manufactured using other techniques, such as EBM (0.15 to 0.25).[41] Key findings of mechanical properties of metallic lattice structures fabricated using SLM are tabulated in Table 2.

Biological applications of scaffolds by selective laser melting

SLM metallic scaffolds can be used as permanent implants for bone tissue engineering in load-bearing applications. Porosity is an essential condition for osteo-induction. However, there is a limit to which osteo-inductive potential can be increased by increasing the porosity of the scaffolds as they need to be mechanically stable in order to facilitate new bone formation.[42-45] The pores also have to be interconnected in order to ensure bone ingrowth.[43,46] Details of the biological response of metallic scaffolds have been reviewed recently by Sing *et al.*[47]

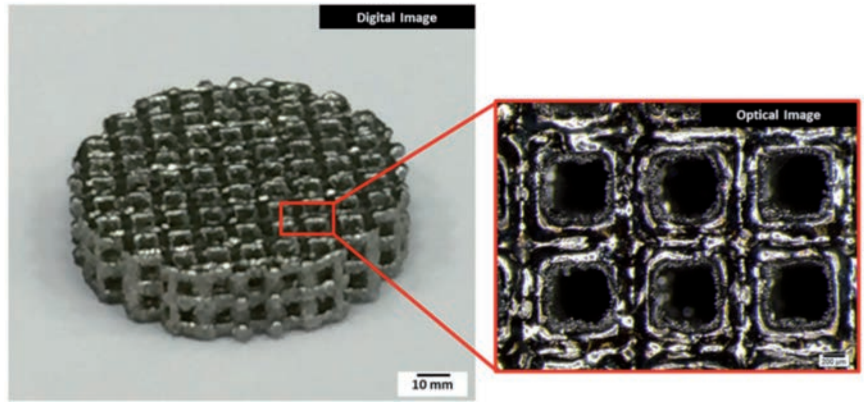

Figure 4. Metallic scaffold fabricated by selective laser melting: overall scaffold (digital image, left) and its magnification (optical image, right).

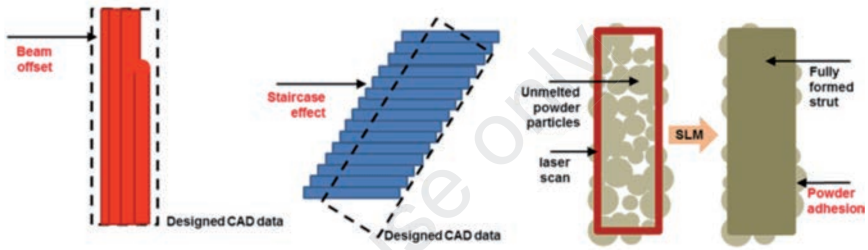

Figure 5. Causes of inaccuracy of production of the designed lattice structures by selective laser melting.

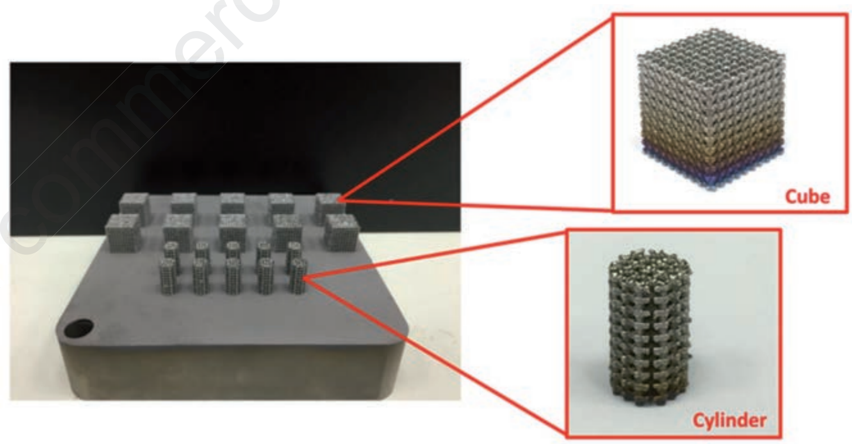

Figure 6. Compression test coupons fabricated by selective laser melting.

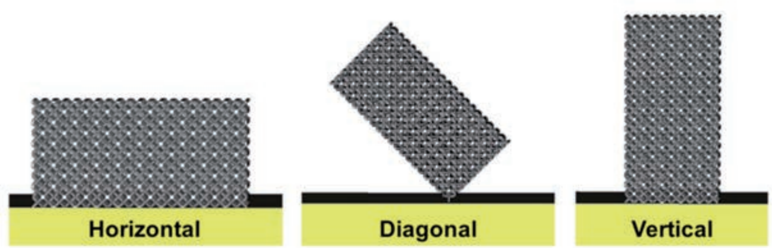

Figure 7. Build orientations of lattice structures in selective laser melting.

Conclusions

SLM allows the fabrication of metallic scaffolds with virtually any designs for load-bearing and biological functions. However, there are still research challenges to overcome in order to fully exploit the opportunities of this technology. In particular, both manufacturability and mechanical testing could be improved. Although SLM claims to provide the capability of structures with any possible design, not all virtual designs can be translated into actual products by SLM. Some of the limitations of the process include the need for support structures for the overhanging struts in the scaffolds when the unit cells have a large size and powder adhesion on the struts. However, these limitations can be overcome by proper process control by suitable design and/or by selection of proper processing parameters, such as laser power. Currently, there is no standard procedure for the mechanical characterization of the lattice structures obtained by SLM, and standards such as ASTM E9 and/or ISO 13314-2011 have been adapted. However, as the technology gains more attention, a specific standard for scaffold performance characterization is needed, especially for scaffolds with wide unit cells design.

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