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Control of structural and mechanical properties in bioceramic bone substitutes via additive manufacturing layer stacking orientation

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Abstract

Additive manufacturing (AM) is a promising approach for fabricating structures to serve as bone substitutes, or as biomaterial components in biphasic implants for repair of osteochondral defects. In this study, the three dimensional printing (3DP) AM process was investigated to determine the effect of powder layer orientation on mechanical and structural properties of fabricated parts. Five types of standard cylindrical parts were manufactured via AM with 0°, 30°, 45°, 60° and 90° stacking layer orientations relative to the vertical z-axis of the print bed, using amorphous calcium polyphosphate (CPP) powder of irregular particle shape, average aspect ratio ≈ 1.70 and particle size between 75 and 150 μm. It was concluded that layer orientation had an effect on porosity and compressive strength, based on induced powder particle orientation in the green part during powder layering. The resulting bulk porosity values ranged between $30.0 \pm 2.4\%$ and $38.2 \pm 2.7\%$, while the compressive strength ranged between 13.50 ± 1.95 MPa and 45.13 ± 6.82 MPa. The orientation with the highest compressive strength was 90°, while orientations with the weakest compressive strength were 0° and 45°. Based on these results, it was established that AM-made parts are structurally and mechanically anisotropic. The stacking layer orientation which results in the highest strength performance along a preferred loading orientation can be implemented to further optimize mechanical strength of constructs along the maximum loading direction.

Keywords: Additive manufacturing; 3D printing; Oriented layering; Calcium polyphosphate; Bioceramic bone substitutes

1. Introduction

Porous bone substitutes serve as an artificial matrix providing the mechanical and structural template for new bone formation. Such porous structures must be biocompatible and ideally should promote osteogenesis by being osteoconductive and osteoinductive while degrading in vivo at an appropriate rate to allow their replacement by newly formed bone [1,2]. The porous structure must also be designed to have an anatomically accurate three dimensional (3D) shape in order to maintain a natural contact load distribution post implantation [3] and initial internal structure in terms of micro- and macro-interconnected porosity to promote cell proliferation, metabolic exchange and vascularization [4]. Furthermore, the mechanical strength and porous architecture of the bone substitute should ideally be designed to match the load bearing requirements at the substitution site and to promote the appropriate bone growth cues as dictated by mechanostat theory [5]. Ideally, this would suggest anisotropic structural and mechanical characteristics throughout the construct, depending on the implantation site.

Powder-based additive manufacturing (AM) utilizing three dimensional printing (3DP) is a very promising fabrication method for making scaffolds or porous constructs in the field of tissue engineering and regenerative medicine, and specifically for bone substitute fabrication [2,6–10]. Using this approach, the anatomical shape and internal porous configuration of the implant is first designed in a computer-aided design (CAD) environment. Subsequently, the CAD model is converted into image slices and the scaffold is manufactured in a layer-by-layer fashion by repeated stacking powder layers and subsequently

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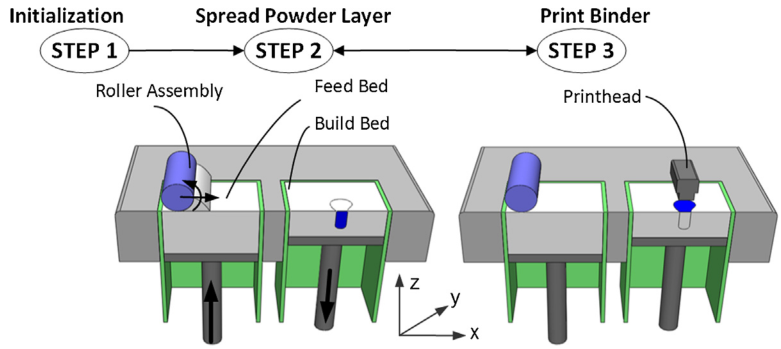

Fig. 1. Process description for conventional AM via powder-based 3DP.

injecting a binder solution at locations dictated by the cross-sectional image of the part layer to be formed as shown in Fig. 1. The resulting product is referred to as a green part. For ceramic structures, such as the calcium polyphosphate (CPP) used in the present study, further post-green part processing, usually involving thermal annealing, is necessary to achieve required strength properties and structural characteristics (i.e. % porosity, pore size and interconnectedness) of the final part [4,8].

Prior investigations by a number of groups have focused on fine-tuning 3DP process parameters to examine their effect on mechanical and structural properties of the final product. The appropriate binder–powder material systems compatible with both the additive manufacturing process and the biological requirements of the bone substitute were investigated [2,11]. Other studies have examined the effect of the liquid binder used during powder lay-up and green part formation with regard to its chemical composition [12,13], concentration [10,12,13] and saturation levels [14–16] to determine appropriate binder–powder interactions that would produce samples with a desired compressive and flexural strength and porosity [10,12,13,15]. Other studies have focused on defining powder composition and blends to yield better powder flow characteristics [17,18] and improved mechanical performance of the final structure [12]. The effect of powder particle size and its effect on physical, structural and mechanical properties of AM-formed constructs has also been studied [19]. Layer thickness is another parameter that can be controlled during the 3DP process, with a range of layer thicknesses having been used for preparation of samples in order to study the effect on mechanical properties [15]. These studies concluded that, in general, the flexural and compressive strength performance is inversely proportional to layer thickness [15,20]. The effect of including open or closed macro-channels within the porous structures during the 3DP processing and its effect on mechanical strength and biological response of porous constructs has also been studied [12,19,21–24]. In this context, a new type of 3DP platform has been investigated, capable of creating interconnected macro-channels with a feature size below 500 μm within the part while avoiding the risk of having particles trapped within the macro-channels [25,26].

In 3DP, due to the nature of the layer-by-layer manufacturing process, the effect of layer stacking orientation within the part may influence the physical, structural and mechanical properties of constructs so formed. Shanjani et al. [27] and Zhang et al. [20] studied the effect of layer orientation along the direction of the printing axes and concluded that mechanical strength characteristics were related to orientations used in forming parts. This effect has not been explored in detail, as the two previously reported studies focused only on orientations along the printing axes x, y, z, without considering intermediate orientations. In the present study, to better understand the correlation between layer orientation and mechanical properties, standard cylindrical parts with 0°, 30°, 45°, 60°, and 90° layer stacking orientations with respect to the vertical axis (z-axis) in the build chamber were fabricated and characterized in terms of porosity, bulk density, and compressive strength. It is proposed that the stacking layer orientation within a part which results in the highest strength can be aligned during part fabrication in the direction of anticipated maximum loading, if this is known during the design stage. Or, contrarily, the orientation resulting in the lowest strength can be avoided from coinciding with expected high load-carrying directions.

2. Materials and methods

2.1. Materials

In this study, the powder material used in the AM process was amorphous calcium polyphosphate (CPP) powder formed as reported in earlier studies [28]. The powder is characterized by an irregular particle shape, an aspect ratio ≈1.70 and particle size range between 75 and 150 μm. This powder was mixed with polyvinyl alcohol (PVA) powder (Alfa Aesar, Ward Hill, MA) of particle size <63 μm at a composition ratio of 90 wt% CPP and 10 wt% PVA. To ensure a homogeneous blending, the CPP and PVA powders were mixed for 4 h using a rotating jar mill (US Stoneware, OH). The PVA powder served as an additional binding agent in combination with the liquid binder (Zb™58) (3D Systems, Burlington, MA) which also served as an aqueous solvent for the PVA particles to give acceptable green strength to samples formed by 3DP.

2.2. Sample fabrication

Previous studies reported on preparation of porous CPP samples and the effect of CPP powder size and method of porous construct preparation have been reported for conventional gravity