Influence of layer thickness and build orientation on compressive strength of 3D printed scaffolds prototypes

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Abstract. The research on fabrication of customised porous bone scaffolds through additive manufacturing has been gaining momentum since last couple of years. This paper presents an analysis of compressive strength (CS) of two slightly different calcium sulfate based proprietary materials namely, Zp150 and VisiJet PXL Core. The comparison is performed on different layer thickness (LT) and builds orientation (BO) of ZPrinter®450 using full factorial design approach. Initially, a computer aided design (CAD) model of the porous scaffold with designed porosity is prepared in a CAD modelling software and then additive manufacturing is done on four different LT (0.089 mm, 0.101 mm, 0.112 mm and 0.125 mm) and three BO (along x-axis, y-axis and z-axis) of ZPrinter®450. Analysis of CS reveals that prototypes made of VisiJet PXL Core material have shown a better strength in comparison with their Zp150 counterparts for similar LT and BO. In general, prototypes of both the materials printed along x-axis posses better CS for all the LT. Moreover, the prototype of VisiJet PXL Core material fabricated along x-axis on layer thickness 0.089 mm possesses highest (1.17 MPa) CS among all the prototypes.

Key words: 3D printing, Calcium sulfate, Compressive strength, Full factorial design, Porous bone scaffold

1. Introduction

Bone scaffolds have a significant role in bone tissue engineering (BTE). Synthetic bone scaffold comes handy when allograft and autograft procedure becomes very difficult or impossible. The synthetic bone scaffolds have been produced through various traditional techniques [1] for past several years. However, traditional techniques have certain limitations like poor control over micro and macro architecture and difficulty in producing customised shape that perfectly fits the damaged site of a patient. Additive manufacturing (AM) process available since 1980s has shown a good potential to fabricate customised porous bone scaffolds due to its capability to offer precise control on macro structural features at the time of fabrication [2, 3, 4, 5]. 3D printing process, one of the several AM processes, makes use of CAD model to fabricate a physical part by selectively depositing liquid binder through print heads onto ceramic powder in layer by layer manner as shown in Figure 1. It can fabricate customised bone scaffold in ceramic material, a material possesses good biocompatibility and biodegradability.

Compressive strength (CS) matters a lot in bone scaffolding, as it not only specifies the application of scaffold but also decides if the scaffold bears the pressure posed by the growing cells...
during the culturing process [6]. The calcium sulfate based 3D printed scaffold usually does not possess high compressive strength and suitable mainly for in vitro applications. They have limited in vivo applications except the low load conditions [7, 8]. According to Dimitrov et al. (2006), properties of raw material as well as process parameters of the printer affect the final quality of fabricated scaffolds a lot [9]. Optimization of process parameters in a systematic manner proves very helpful in improving the process performance by reducing the variation of the process [10]. Several optimization techniques including design of experiments (DOE) have been explored by many researchers for optimising the performance of AM processes [11]. Onuh and Hon (1998), investigated stereolithography (SLA) process to optimise various build parameters to achieve improved surface finish [12]. Lakshmi and Arumaikkannu (2014), studied effect of printing parameters on surface finish of patient specific bone implants fabricated via selective laser sintering (SLS) process [13]. A few researchers have also studied effect of parameters on surface finish and dimensional accuracy of samples produced using fused deposition modelling process [14, 15]. A limited work is found on optimizing 3D printing parameters for calcium sulfate based composite material. Hsu and Lai (2010), obtained improved dimensional accuracy and flexural strength of additively manufactured parts using Taguchi method [10]. Rai et al. (2018), observed a decrease in tensile strength with increasing thickness of layer for the calcium sulfate samples [16]. Apart from this, a few researchers [17, 18] also reported considerable improvement in properties of 3D printed parts through optimisation of process parameters.

![Figure 1. Schematic diagram of 3D printing](image-url)

As mentioned above, raw material and process parameter levels significantly affect the CS of the 3D printed parts; there is always a room for evaluating CS of porous scaffolds in view of availability of new material. The objective of this study is to optimize the effect of layer thickness (LT) and build orientation (BO) of ZPrinter®450 for compressive strength of porous bone scaffolds made of Zp150 and newly available VisiJet PXL Core material using full factorial design of experiment approach.

2. Materials and Methods

2.1 Materials

Calcium sulfate based ceramic composite material Zp150 and VisiJet PXL Core (VJ PXL) has been considered for this study. A sieve shaker is employed for particle size distributions of both the materials. From the particle size distribution chart shown in Figure 2, it can be clearly seen that VisiJet powder is slightly fine grained compared to Zp150 powder. More than 75 % grains of VisiJet powder
are smaller than 75 μm; whereas, only about 55% of the grains of Zp150 powder are smaller than 75 μm. A water based binder zb63 is used in printing of the porous scaffold prototypes.

2.2 CAD model

In order to test compressive strength, a CAD model of size 8 mm x 8 mm x 12 mm as shown in Figure 3, is designed in SolidWorks® 2016. To introduce porosity, through pores of 600 μm diameters have been made on mutually perpendicular sides with minimum distance of 600 μm between two pores.

2.3 Experimentation

The compressive strength of fabricated scaffolds depends on raw material as well as on process parameters of the 3D printer. Literature survey reveals that layer thickness and build orientation are the most influential parameters in affecting build quality of the parts [18]. Hence, a full factorial design of experiment approach is chosen to study the effect of layer thickness and build orientation of ZPrinter®450 on compressive strength of the scaffolds made of Zp150 and VisiJet PXL Core (VJ PXL) materials. Materials and process parameters under study are shown in Table 1.
The CAD model of scaffold in STL format is first loaded onto Magics RP software to remove any error occurred during file conversion and then loaded into ZPrint®, proprietary software of 3D Systems for build preparation. One copy of the CAD model is placed along x-, y- and z-axis. On the basis of Table 1, total 24 scaffold prototypes, 12 for each material are fabricated on ZPrinter®450. After fabrication, prototypes are taken out and cleaned using air wand. All the prototypes are used as green part only; no infiltration is done to add extra strength. Figure 4, shows the photographs of build chamber of ZPrinter®450 and fabricated scaffold prototypes. The compressive strength (CS) of all the 24 pieces (3 pieces / LT x LT x 2 materials) is measured using Universal testing machine of loading capacity 5 KN.

**Table 1. Parameters with levels considered for the study**

| Parameters                  | Level 1 | Level 2 | Level 3 | Level 4 |
|-----------------------------|---------|---------|---------|---------|
| Layer thickness (LT) in (mm)| 0.089   | 0.101   | 0.112   | 0.125   |
| Build orientation (BO)      | along x-axis | along y-axis | along z-axis | - |
| Materials                   | VJ PXL  | Zp150   | -       | -       |

**Figure 3. CAD model of the scaffold**

The CAD model of scaffold is shown in Figure 3.
3. Result and Discussion

Compressive strength (CS) of all the 24 prototypes is summarised in Table 2. Figure 5 displays line chart to show the trend of CS of samples printed along x-, y- and z-axis for different LT. A careful observation of the Table 2 and Line chart shown in Figure 5 reveals that for both the materials, VJ PXL and Zp150, highest compressive strength is measured for prototypes fabricated along x-axis and 0.089 mm LT. The highest CS for VJ PXL material is found equal to 1.17 MPa and 1.11 MPa for Zp150 powder. Lowest CS for both the materials has been measured as 0.77 MPa and 0.74 MPa respectively for prototypes fabricated along y-axis at LT 0.125 mm.

| Material | Orientations | LT_0.089 mm | LT_0.102 mm | LT_0.112 mm | LT_0.125 mm |
|----------|--------------|--------------|--------------|--------------|--------------|
| VJ PXL   | along x-axis  | 1.17         | 1.1          | 0.96         | 0.91         |
|          | along y-axis  | 0.96         | 0.9          | 0.82         | 0.77         |
|          | along z-axis  | 1.09         | 0.98         | 0.83         | 0.79         |
| Zp150    | along x-axis  | 1.11         | 1.07         | 0.91         | 0.86         |
|          | along y-axis  | 0.95         | 0.91         | 0.81         | 0.74         |
|          | along z-axis  | 1.05         | 0.95         | 0.89         | 0.75         |
In general, prototypes fabricated along x-axis possess better CS in comparison with prototypes fabricated along y- and z-axis. The prototypes fabricated along z-axis found to possess better CS than samples fabricated along y-axis. Overall, prototypes of VJ PXL powder have shown better CS in comparison with prototypes of Zp150 powder for corresponding LT and BO barring a few exceptions. In terms of LT, most of the samples have shown a better CS for lower LT, which decreases with increasing LT. The decreasing CS with increasing LT may be due to uneven curing of thicker powder layers. The layers are printed as continuous strips along x-axis, and in laminated fashion along z-axis. This may be the possible reason behind higher CS along these axes. The fabrications in bands along with layers are responsible for lowest CS along z-axis.

4. Conclusions

This study aims at optimising material and parameters of ZPrinter®450, a 3D printer for compressive strength of scaffolds made of calcium sulfate based materials. A full factorial design of experiment approach has been employed to optimise the effect of LT and BO of ZPrinter®450 for porous bone scaffolds made from two slightly different powder materials. The conclusions of the study are summarised as below:

- From the materials under consideration, VJ PXL powder has shown better results in terms of CS when compared with Zp150 powder. The scaffolds of VJ PXL material fabricated along x-axis at 0.089 mm layer thickness is found to possess highest CS (1.17 MPa) among all the prototypes.
- It has also been observed that irrespective of the materials, prototypes fabricated along x-axis have shown higher CS than y- and z-axis for corresponding layer thicknesses.
- Based on the CS obtained, these scaffolds may not be suitable for in vivo applications involving considerable loading conditions; however, they may be used for in vitro as well as in vivo applications with no or very low load bearing conditions.

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References

[1] Bose S, Vahahzadeh S and Bandyopadhyay A 2013 Bone tissue engineering using 3D printing. Mater. Today. 16(12) 496-504
[2] Giamitelli S M, Accoto D, Trombetta M and Rainer A 2014 Current trends in the design of scaffolds for computer-aided tissue engineering. Acta Biomater. 10(2) 580-94
[3] Sears N A, Seshadri D R, Dhavalikar P S and Cosgripp-Hernandez E 2016 A review of three-dimensional printing in tissue engineering. Tissue Eng. Part B Rev. 22(4) 298-310
[4] Rosetti L, Parisi V, Petretta M, Cavallo C, Desando G, Bartolotti I and Grigolo B 2017 Scaffolds for bone tissue engineering: state of the art and new perspectives. Mater. Sci. Eng. C 78 1246-62
[5] Modi Y K 2018 Calcium sulphate based 3D printed tooling for vacuum forming of medical devices: An experimental evaluation. Mater Technol. 33(10) 642-50
[6] Sahu K K and Modi Y K 2020 Investigation on dimensional accuracy, compressive strength and measured porosity of additively manufactured calcium sulphate porous bone scaffolds. Mater Technol. 1-12
[7] Brunello G, Sivolella S, Meneghello R, Ferroni L, Gardin C, Piattelli A, Zavan B and Bressan E 2016 Powder-based 3D printing for bone tissue engineering. Biotechnol. Adv. 34(5) 740-53
[8] Zhang L, Yang G, Johnson B N and Jia X 2019 Three-dimensional (3D) printed scaffold and material selection for bone repair. Acta Biomater. 84 16-33
[9] Dimitrov D, Schreve K and de Beer N 2006 Advances in three dimensional printing—state of the art and future perspectives. Rapid Prototyp. J. 12(3) 136-47
[10] Hsu T J and Lai W H 2010 Manufacturing parts optimization in the three-dimensional printing process by the Taguchi method. J Chin Inst Eng. 33(1) 121-30
[11] Montgomery D C 2017. Design and analysis of experiments. John wiley & sons
[12] Onuh S O and Hon K K B 1998 Optimising build parameters for improved surface finish in stereolithography. Int. J. Mach. Tools Manuf. 38(4) 329-42
[13] Lakshmi K S and Arumaikkannu G 2014 Influence of process parameters on surface finish in customized bone implant using selective laser sintering. Adv Mat Res. 845 862-67
[14] Sood A K, Ohdar R K and Mahapatra S S 2009 Improving dimensional accuracy of fused deposition modelling processed part using grey Taguchi method. Mater. Des. 30(10) 4243-52
[15] Srivastava M and Rathee S 2018 Optimisation of FDM process parameters by Taguchi method for imparting customised properties to components. Virtual Phys Prototyp. 13(3) 203-10
[16] Rai H V, Modi Y K and Pare A 2018 Process parameter optimization for tensile strength of 3D printed parts using response surface methodology. In IOP conf. ser. Mater. sci. eng. 377 012027
[17] Farzadi A, Waran V, Solati-Hashjin M, Rahman Z A A, Asadi M and Osman N A A 2015 Effect of layer printing delay on mechanical properties and dimensional accuracy of 3D printed porous prototypes in bone tissue engineering. Ceram. Int. 41(7) 8320-30
[18] Asadi-Eydivand M, Solati-Hashjin M, Farzad A and Osman N A A 2016 Effect of technical parameters on porous structure and strength of 3D printed calcium sulfate prototypes. Robot Comput Integr Manuf. 37 57-67