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Modelling of porosity of 3D printed ceramic prostheses with grid structure

I. Buj-Corral[a,]*, O. Petit-Rojo[a], A. Bagheri[a], J. Minguella-Canela[b]

[a]Universitat Politècnica de Catalunya /(UPC), Department of Mechanical Engineering, School of Engineering of Barcelona (ETSEIB). Av. Diagonal, 647. 08028. Barclona, Spain
[b]Fundació CIM-UPC. Llorenç i Artigas, 12.08028, Barcelona, Spain

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Abstract

Fixation of ceramic prostheses by means of osteointegration implies use of porous structures in which bone tissues can grow. Such structures require total porosity values between 50 and 75 %, and pore size values between 100 and 500 µm. It is possible to manufacture scaffolds that comply with porosity requirements by means of 3D printing processes like Fused Filament Fabrication (FFF). However, such printing technology does not allow to directly select pore size and porosity value to be obtained. On the contrary, process variables such as layer height, nozzle diameter, infill, speed, etc. need to be selected before printing. Main objective of the present work is to define a model that helps selecting appropriate values for printing variables in order to obtain required porosity and pore size values. Such model will be applied to grid structures. In a first step, relationship was searched between pore size and three process variables: layer height, nozzle diameter and infill. In a further step, curves for pore size as a function of infill were searched for the three usual nozzle diameters employed for printing ceramics, 150, 250 and 410 µm. Finally, pore size and infill were determined for mean pore size of 300 µm. Results showed that the higher nozzle diameter, the lower infill should be.

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Keywords: 3D printing, grid, porosity, pore size, scaffold

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1. Introduction

Ceramics are common materials employed for manufacturing prostheses, since, as a general trend, they provide low abrasion combined with good mechanical properties. However, it is difficult to produce ceramic prostheses that comply with users' specifications regarding geometry and structure, since ceramics are hard and fragile, and thus

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difficult to be machined. In addition, in order to fix the prostheses by means of osteointegration, it is recommended to use porous structures that favor tissue growth. Usual requirements for prostheses are: pore size between 100 and 500 µm, and total porosity between 50 and 75 % [1]. Use of 3D printing for ceramic materials can give rise to more complicated structures than machining processes. Different printing techniques have been used in the past for manufacturing ceramic materials, for example selective laser melting (SLM) [2] or polymerization of resin containing ceramics in suspension [3]. In the present research, fused filament fabrication (FFF) technology will be employed for printing prostheses, with ceramic powder mixed with a polymer.

When printing a scaffold, it is not possible to directly select neither pore size nor porosity values. On the contrary, process variables must be selected. Main objective of the present work is to model porosity of grid structure as a function of printing parameters like nozzle diameter, layer height and infill. For doing this, an analytical model was used for searching equations that relate pore size of the structure with infill and diameter. From the model, specific functions were found for three different nozzle diameter considered. Finally, infill and porosity values were determined for mean pore size.

Nomenclature

DEM	discrete element method
FFF	fused filament fabrication
PLA	polylactic acid
SLM	selective laser melting

2. Materials and methods

In the future, complex scaffolds will be printed with hemispherical shapes. In the present work, in order to simplify the printing process, grid structure was investigated in prismatic shapes (Figure 1).

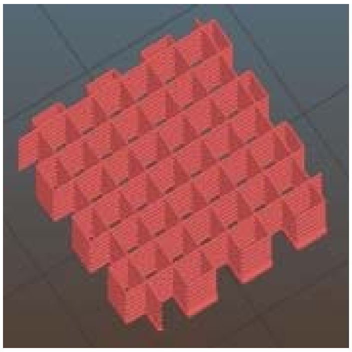

Fig. 1. Grid structure.

As for measurement of porosity in scaffolds, it is possible to determine porosity and pore size of a structure from its 3D representation. For example, Dupuy et al. used a program to obtain cumulated distribution of pore size and porosity from a 3D image [4]. Barui et al. assessed porosity of printed scaffolds from images obtained by micro-computed tomography [5]. Regarding modeling of porosity, Guan et al. employed a numerical model based on Discrete Element Method (DEM) to simulate porosity and pore size after sintering process of ceramic membranes [6]. Montazerian et al. studied the effect of pore size and porosity of 3D printed scaffolds on their permeability [7]. In the present paper, a new methodology is presented for determining porosity as a function of printing parameters. Different steps of the methodology are presented in Figure 2.

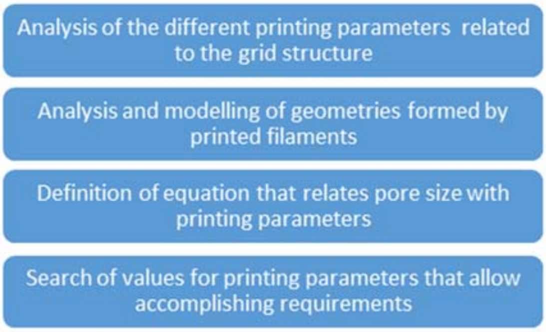

Fig. 2. Methodology used for measuring porosity.

- Step 1. Three process parameters were studied: nozzle diameter, layer height and infill. Nozzle diameters have standardized values of 150, 250 and 410 µm. Layer height can be selected by the user with the only restriction of being lower than nozzle diameter. Infill can be also selected by user.
- Step 2. As for analysis and modelling of grid structure, geometry of printed filament was taken into account [8].
- Step 3. A general equation was found for pore size as a function of infill, nozzle diameter and layer height. Later, specific curves were obtained for pore size vs. infill, for each one of the three usual nozzle diameters employed in the 3D printing process of ceramics. For this purpose, Matlab software was employed.
- Step 4. Values for printing parameters were searched from the curves obtained in Step 3, for the required mean pore size value.

3. Results

3.1. Model for porosity

Infill of a printed structure is defined in Equation 1 as the degree of filling of the printed part.

$$\text{Infill} = \frac{\text{Volume of printed material}}{\text{Total volume of part}} \tag{1}$$

Porosity is the proportion of voids within the total volume of the printed part (Equation 2).

$$\text{Porosity} = \frac{\text{Volume of voids}}{\text{Total volume of part}} \tag{2}$$

Total volume of part is equal to the summation of infill and porosity. Thus, infill is related to porosity as stated in Equation 3.

$$\text{Infill} = 1 - \text{Porosity} \tag{3}$$

In the present work, since porosity of prostheses is to be comprised between 50 and 75 %, infill should be included within interval [25, 50] %.

Layer height must be lower than nozzle diameter. Thus, upper bound for layer height is nozzle diameter. Lower bound for layer height depends on type of material printed and nozzle diameter. For example, for PLA with nozzle diameter 0.4 mm, it is recommended not to use a layer height value lower than 0.25 mm.

Regarding the way the material is deposited on the printer base, geometry of the printed filaments changes in contact with the base of the printer. For this reason, it is proposed to model geometry of the filaments as rectangles with one semicircle at each side [8]. The condition to be accomplished is that extrusion width is higher than layer height (Figure 3).

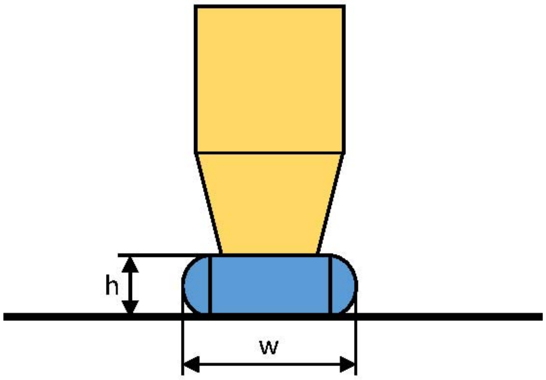

Fig. 3. Geometry of standard filaments.

Thus, required volume to obtain this geometry per length unit (or area of printed filament) is obtained by addition of the area of a rectangle plus a circle, as stated in Equation 4.

$$\text{Area of printed filament} = (w - h)\cdot h + \pi\cdot\left(\frac{h}{2}\right)^2 \tag{4}$$

Where w is extrusion width (mm), and h is layer height (mm).

If the user does not select a specific width value, the program will calculate width that minimizes forces. This corresponds to the situation where area of printed filament (Equation 4) is equal to area of unprinted filament (Equation 5), where d is filament diameter in mm.

$$\text{Area of unprinted filament} = \pi\cdot\left(\frac{d}{2}\right)^2 \tag{5}$$

Equation 6 can be derived from Equations 4 and 5.

$$\pi\cdot\left(\frac{d}{2}\right)^2 = (w - h)\cdot h + \pi\cdot\left(\frac{h}{2}\right)^2 \tag{6}$$

Extrusion width w can be calculated as a function of layer height h in mm and filament diameter d in mm (Equation 7).

$$w = \frac{\pi \cdot (\frac{d}{2})^2 + (4 - \pi) \cdot (\frac{h}{2})^2}{h} \tag{7}$$

If filaments are placed one next to the other, without overlap, paths will be tangent and there will be empty space between filaments, corresponding to the gray area. Thus, it will not be possible to obtain solid geometries (Figure 4). In this case, distance between trajectories is equal to extrusion width.

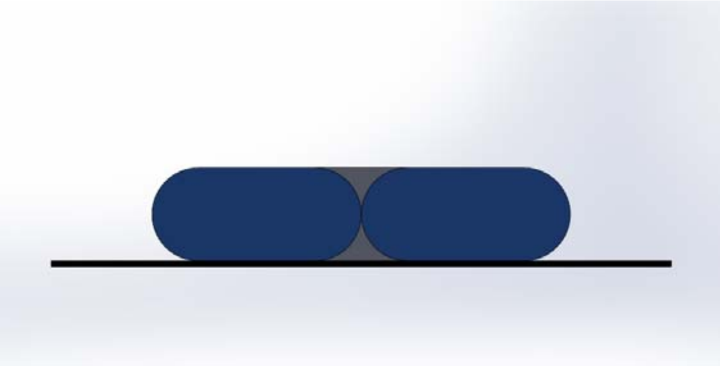

Fig. 4. Geometry obtained when distance between trajectories is equal to extrusion width.

In order to obtain a solid figure, it is necessary to reduce distance between parallel trajectories. For this reason, distance between trajectories needs to be lower than extrusion width w when infill 1 is selected, in order fill the void space (Equation 8).

$$w = \text{nozzediameter} \cdot 105 \tag{8}$$

In general, distance between extrusion trajectories is higher than extrusion width w (Figure 5).

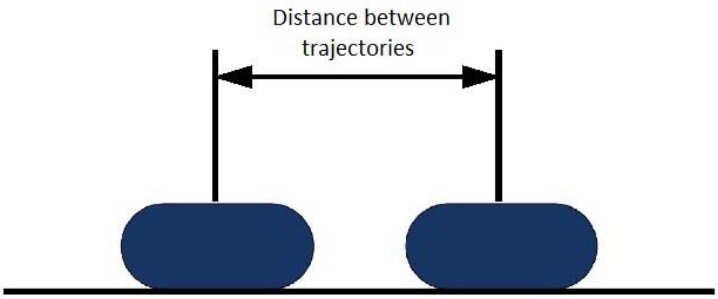

Fig. 5. Position of filaments and distance between trajectories for the grid pattern.

Definition of infill is used to find distance between parallel trajectories of the grid pattern (Equation 9). Volume of printed part is related to Area of printed filament, assuming h^2 to be close to zero. Total volume of the part is related to distance between trajectories of the grid pattern.

$$\text{Infill} = \frac{\text{Volume of printed material}}{\text{Total volume of part}} = \frac{w \cdot h}{\text{Distance between trajectories of the grid pattern} \cdot h} \tag{9}$$

If terms are joined, equation 10 is obtained.

$$\text{Distance between trajectories of the grid pattern} = \frac{w}{\text{Infill}} \tag{10}$$

Once the distance between trajectories has been found, it is necessary to subtract the width of the filament in order to find pore diameter (Equation 11).

$$\text{Pore size} = \text{Distance between trajectories of the grid pattern} = \frac{w}{\text{Infill}} \tag{11}$$

If all equations are combined, a new equation is obtained, in which pore diameter is found as a function of infill, layer height and nozzle diameter (Equation 12).

$$\text{Pore size} = \frac{1}{h} \cdot \left(\left(\frac{1}{\text{infill}} - 1\right) \cdot \left(\pi \cdot \left(\frac{d}{2}\right)^2 \cdot (4-\pi) \cdot \left(\frac{h}{2}\right)^2\right)\right) \tag{12}$$

For ceramic materials it has been proven that optimum layer height that gives best printing quality depends on nozzle diameter (Equation 13).

$$h_{opt} = 0.9 \cdot d \tag{13}$$

This means that there is a linear relationship between optimal layer height and nozzle diameter. If equation 12 is substituted in equation 11, a new equation is obtained with only infill and nozzle diameter as parameters (Equation 14).

$$\text{Pore size} = \frac{1}{0.9 \cdot d} \cdot \left(\left(\frac{1}{\text{infill}} - 1\right) \cdot \left(\pi \cdot \left(\frac{d}{2}\right)^2 \cdot (4-\pi) \cdot \left(\frac{0.9 \cdot d}{2}\right)^2\right)\right) \tag{14}$$

Pore size should be comprised between 100 and 500 µm. With Eq. 14 theoretical value for pore size is obtained. When the grid will be printed, pore size will have certain variability around theoretical value. Pore size distribution is symmetrical. For this reason, if maximum number of pore sizes should be comprised within interval, pore size should be fixed in the mean value of the interval (0.300 mm).

3.2. Curves for pore size

Pore size vs. infill curves were obtained for the three usual nozzle diameters (0.150 mm, 0.250 mm and 0.410 mm) (Figure 6).

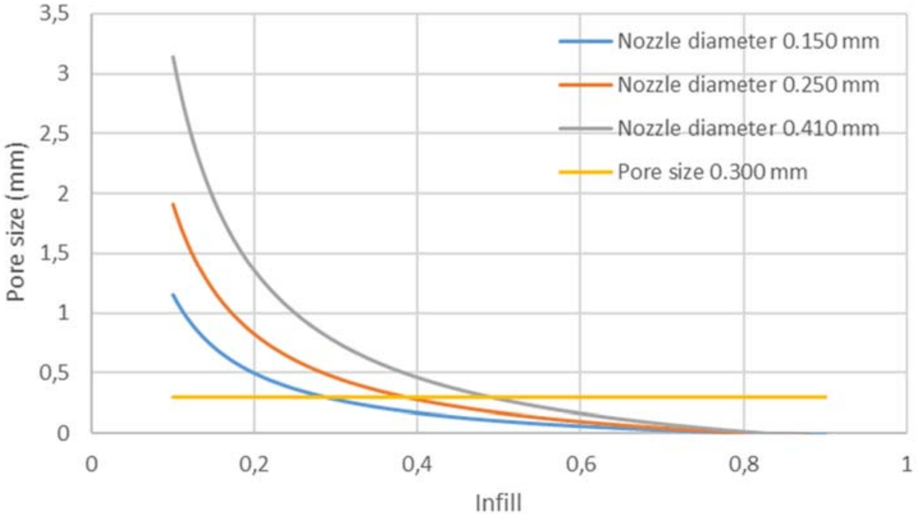

Fig. 6. Pore size vs. Infill for different nozzle diameters.

The higher nozzle diameter, the higher pore size is. Pore size decreases with infill as expected. A straight line corresponding to pore size 0.300 mm was added to the figure.

The three curves show a vertical asymptote for infill 0. This may be attributed to the fact that, when infill=0, no material is used and, for this reason, pore size tends to be infinite, since the whole part will be a pore. Highest infill value to be selected with Slic3r is 1. With infill=1 there is no pore, since the part is solid. If a value of 1 is introduced in the equation for infill, pore size will take negative values. This result is coherent, since a correction for parallel trajectories was applied so that the material will be superimposed in order to obtain structures that are 100 % solid.

In Table 1 results of intersection between curves for different nozzle diameters and the straight line for pore size 0.300 mm are presented.

Table 1. Values for nozzle diameters and infill for pore size 0.300 mm.

Structure number	Theoretical pore size (mm)	Nozzle diameter (mm)	Infill	Porosity
1	0.300	0.150	0.285	0.715
2	0.300	0.250	0.385	0.615
3	0.300	0.410	0.486	0.514

In order to obtain theoretical pore size of 0.300 mm, the higher nozzle diameter, the higher infill needs to be selected. In all cases, porosity is included within interval [0.50, 0.75] % as required.

4. Conclusions

In the present paper a methodology for modeling pore size in 3D printed scaffolds used in ceramic prostheses is presented. First, main process parameters were selected. Second, an equation was searched for pore size as a function of infill, nozzle diameter and layer height. Third, the equation was simplified and curves were obtained for pore size as a function of infill, for three different nozzle diameters. Finally, specific infill values were determined that allow obtaining required mean pore size value.

It was observed that, the higher nozzle diameter, the higher infill is to be selected in order to obtain a certain mean pore size value. In all cases, total porosity is included within interval of required values for the prostheses.

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References

[1] V. Karageorgiou, D. Kaplan. Biomat. 26, 27, (2005) 5474-5491.
[2] Y.C. Hagedorn, J. Wilkes, W. Meiners, K. Wissenbach, R. Poprawe. Phys. Proc. 5B, (2010) 587-594.
[3] A. Licciulli, C. Esposito, A. Greco, A. Maffezzoli. J Eur Ceram Soc. 24(15) (2004) 3769-3777.
[4] P.M. Dupuy, P. Austin, G.W. Delaney, M.P. Schwartz. Comput. Phys. Commun. 182(10) (2011) 2249-2258.
[5] S. Barui, S. Chatterjee, S. Mandal, A. Kumar, B. Basu. Mat. Sci. Eng. C-Mater. 70 (2017) 812-823.
[6] K. Guan, W. Qin, Y. Liu, X. Yin, C. Peng, M. Lv, S. Qian, J. Wu. Membrane Sci. 520 (2016) 166-175.
[7] H. Montazerian, M. Zhianmanesh, E. Davoodi, A.S. Milani, M. Hoorfar. Mater. Des. 122 (2017) 146–156.
[8] Slic3r manual. http://manual.slic3r.org/advanced/flow-math. Retrieved on 29/11/16.