Materials Science and Engineering C 56 (2015) 444–450

Contents lists available at ScienceDirect

Materials Science and Engineering C

journal homepage: www.elsevier.com/locate/msec

Simple method to generate and fabricate stochastic porous scaffolds

Nan Yang *, Lilan Gao, Kuntao Zhou

Tianjin Key Laboratory of the Design and Intelligent Control of the Advanced Mechatronical System, Tianjin University of Technology, Binshuixi Road No. 391, Xiqing District, Tianjin 300384, China

ARTICLE INFO

Article history:
Received 14 November 2014
Received in revised form 4 March 2015
Accepted 22 June 2015
Available online 27 June 2015

Keywords:
Stochastic porous scaffold
Function-based method
Additive manufacturing

ABSTRACT

Considerable effort has been made to generate regular porous structures (RPSs) using function-based methods, although little effort has been made for constructing stochastic porous structures (SPSs) using the same methods. In this short communication, we propose a straightforward method for SPS construction that is simple in terms of methodology and the operations used. Using our method, we can obtain a SPS with functionally graded, heterogeneous and interconnected pores, target pore size and porosity distributions, which are useful for applications in tissue engineering. The resulting SPS models can be directly fabricated using additive manufacturing (AM) techniques.

1. Introduction

Porous structures have recently become increasingly important, particularly for medical applications. In contrast to solid structures, porous structures typically have larger internal surface areas and higher strength-to-weight ratios [1], their interconnected pores can govern cell attachment [2], and they provide efficient cell seeding into a scaffold [3], the mass transfer metabolites [4], the delivery drugs or growth factors [5], and a sufficient regeneration space for newly formed tissue [6].

Traditional methods were used to fabricate stochastic porous scaffolds, such as salt leaching [7], gas-foaming [8], freeze-drying [9], and so on. However, these methods failed to accurately control pore properties including interconnectivities, sizes, and porosities [10].

To overcome these limitations, there has recently been some research on computer-aided design method for constructing stochastic porous structures (SPSs), but the methods were complex. Kou and Tan [11] used Voronoi vertices as the control points of a closed B-spline curve to create a cell. This method first obtained convex shaped cells duo to the properties of Voronoi diagram, and then required merging some adjacent cells to create a concave shaped cell. Thus, their algorithm was quite complex and might not be sufficiently flexible for constructing a SPS with a complex external shape. Nachtrab et al. [12] also used a Voronoi-based method for constructing a SPS. The solid phase of a network solid was defined as the set of all those points in space whose distance to the nearest network edge was less or equal to the cylinder radius, but this method may not flexibly construct functionally gradient porosities. Feng et al. [13] reconstructed two-phase composite materials using Gaussian random fields. The resulting structure met a binary-valued marginal probability distribution function.

Currently, a simple function-based method is used to describe pore geometries: a triply periodic minimal surface (TPMS) [14–19]. Compared with the above complex CAD methods, this method can simply use trigonometric implicit functions to derive a complex porous structure. However, based on current efforts, this method focuses on regular porous structures (RPSs) and RPSs with very simple functionally gradient pores. Furthermore, RPSs are quite different from the natural counterparts that are intended to be replaced and did not have some desired properties which SPSs can provide, including good mechanical, thermal, or other physical properties [20].

In this short communication, we extended our previous work [21] for constructing and fabricating SPSs. We could generate a SPS with (1) heterogeneous and interconnected pores, (2) functionally gradient pores, and (3) target porosity and pore size distributions, and keep the overall operations simple. When imported as STL files, the resulting models could be directly fabricated using AM techniques [22–24].

2. Material and methods

The core of generating a SPS is replacing the fixed parameters of a RPS model with random functions.

2.1. Functions representing a RPS

A RPS is defined by

$$\phi(ax, by, cz, e_x, e_y, e_z, d) \leq 0. \quad (1)$$

This inequality defines the 3D solid part for the structure. a, b, and c control the pore sizes in the x, y, and z directions, respectively. For

* Corresponding author.
E-mail address: y79nzw@163.com (N. Yang).

http://dx.doi.org/10.1016/j.msec.2015.06.039
0928-4931/

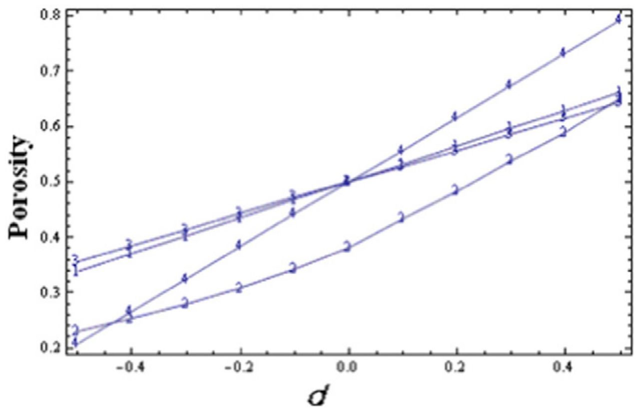

Fig. 1. Relationship between parameter d and porosity. Porosity linearly increases with increasing d for types 1, 2, 3, and 4 TPMS-based RPSs. These four types were defined by $\phi_1(x,y,z) = \cos(ax)\sin(by) + \cos(by)\sin(cz) + \cos(cz)\sin(ax) + d \le 0$ (also type G in [17]); $\phi_2(x,y,z) = \sin(ax)\sin(by) + \sin(by)\sin(cz) + \sin(cz)\sin(ax) + d \le 0$ (also type L); $\phi_3(x,y,z) = \cos(ax)\cos(by) + \cos(cz) + d \le 0$ (also type P); $\phi_4(x,y,z) = \cos(ax)\cos(by)\cos(cz) - \sin(ax)\sin(by)\sin(cz) + d \le 0$ (also type D).

example, in x direction, "a" means that we arrange a cell per $2\pi/a$ unit length. d controls porosity, which is shown in Fig. 1 for the four types of TPMS-based porous structures. e_x, e_y, and e_z are the offset distances in the x, y, and z directions which control the location of the entire structure.

For example, the type P structure can be represented in the full form

$$\phi(ax, by, cz, d, e_x, e_y, e_z) = \cos(ax + e_x) + \cos(by + e_y) + \cos(cz + e_z) + d.$$

2.2. Generating a SPS

In a RPS, a, b, c, e_x, e_y, e_z, and d are all constants. But if we replace these parameters with random functions (such as $f(X)$), then the RPS will be deformed. To construct desired pore size or porosity distributions, random functions need to be generated within given value ranges.

A 3D random function $f(X)$ can be generated by

$$f(X) = \sum_{i=1}^{N} \lambda_i \theta\left(-\frac{\|X - X_i\|^2}{\delta^2}\right) \tag{2}$$

where $X = (x,y,z)$ is the spatial coordinate, and $X_i (i = 1,\ldots,N)$ are the N random points generated within a given 3D scaffold domain D^3. λ_i is a weight coefficient for point X_i, $\theta(.)$ is a basis function, and δ is an adjustable parameter. X_i and λ_i are generated randomly.

However, we cannot assure if the random function generated using Eq. (2) is within a given range. This needs to normalize the function f in the given range $f(X) \in [f_1, f_2]$ for desired pore sizes or porosities. For example, if we intend to control the porosity from 20% to 60% for type 4 structure, then the value range of random function $d(X)$ for ϕ_4 should be from -0.2 to 0.2 as shown in Fig. 1.

Thus, we define operation T[.] for f as

$$T[f(X)] = kf(X) + t \tag{3}$$

where $k = (f_2 - f_1)/(f_{max} - f_{min})$, $t = f_2 - kf_{max}$, and f_{max}, f_{min} are, respectively, a global maximum and minimum of f that are determined by solving

$$\begin{aligned} &\mathrm{Max}(\mathrm{Min}) f(X) \\ &s.t. X \in D^3. \end{aligned} \tag{4}$$

Operation $T[.]$ can be regarded as the optimization processes for target pore sizes and porosities. In this way, we obtain random functions that are all within their own given ranges, such as, $a'(X) \in [a_1, a_2]$, $b'(X) \in [b_1, b_2]$, $c'(X) \in [c_1, c_2]$, $d'(X) \in [d_1, d_2]$, $e_x'(X) \in [e_{x1}, e_{x2}]$, $e_y'(X) \in [e_{y1}, e_{y2}]$, and $e_z'(X) \in [e_{z1}, e_{z2}]$ where $a'(X)$, $b'(X)$, $c'(X)$, $e_x'(X)$, $e_y'(X)$, $e_z'(X)$, and $d'(X)$ are the results of the T[.] operation of random functions $a(X)$, $b(X)$, $c(X)$, $e_x(X)$, $e_y(X)$, $e_z(X)$, and $d(X)$ generated by means of Eq. (2).

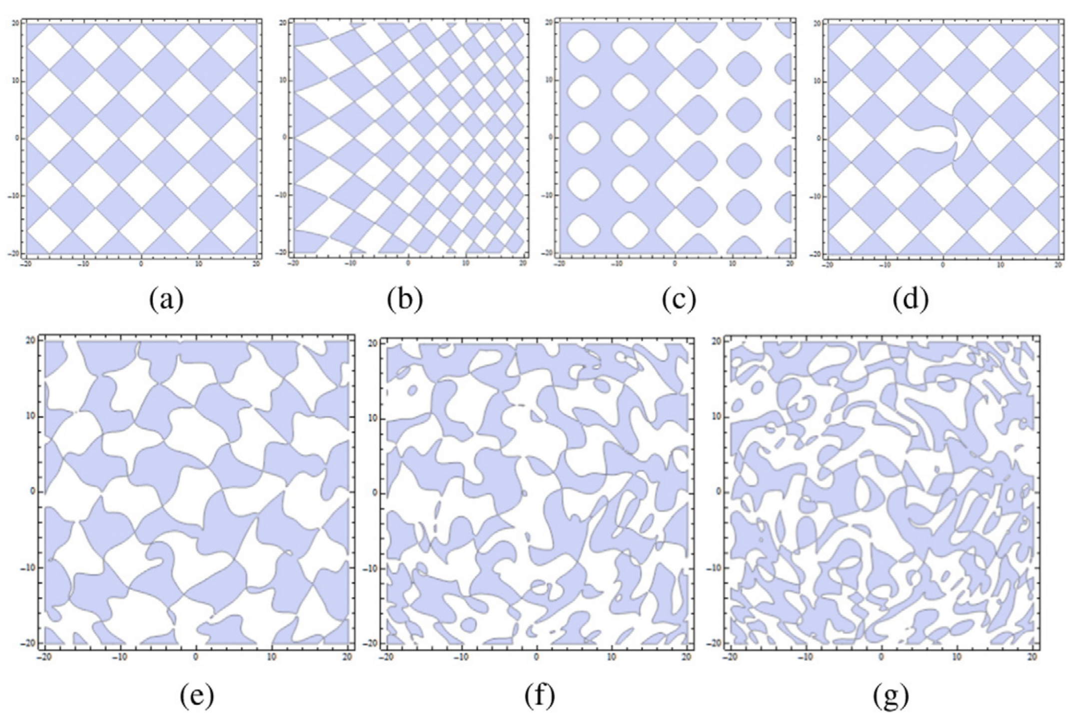

Fig. 2. (a) A 2D regular TPMS-based structure, (b) porous structure with gradient pore sizes, (c) porous structure with gradient porosities, and (d) local deformation; SPSs with different randomized degrees obtained by $e_x, e_y \in [-3,3]$(e), $e_x, e_y \in [-6,6]$(f), and $e_x, e_y \in [-9,9]$(g).