Medical Engineering & Physics 34 (2012) 762–776

Contents lists available at SciVerse ScienceDirect

Medical Engineering & Physics

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

New paradigms in internal architecture design and freeform fabrication of tissue engineering porous scaffolds

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ARTICLE INFO

Article history:
Received 29 February 2012
Received in revised form 4 May 2012
Accepted 11 May 2012

Keywords:
Additive manufacture
Triply periodic minimal surface
Distance fields
3D tissue scaffolds
Freeform fabrication tool path

ABSTRACT

Advanced additive manufacture (AM) techniques are now being developed to fabricate scaffolds with controlled internal pore architectures in the field of tissue engineering. In general, these techniques use a hybrid method which combines computer-aided design (CAD) with computer-aided manufacturing (CAM) tools to design and fabricate complicated three-dimensional (3D) scaffold models. The mathematical descriptions of micro-architectures along with the macro-structures of the 3D scaffold models are limited by current CAD technologies as well as by the difficulty of transferring the designed digital models to standard formats for fabrication. To overcome these difficulties, we have developed an efficient internal pore architecture design system based on triply periodic minimal surface (TPMS) unit cell libraries and associated computational methods to assemble TPMS unit cells into an entire scaffold model. In addition, we have developed a process planning technique based on TPMS internal architecture pattern of unit cells to generate tool paths for freeform fabrication of tissue engineering porous scaffolds.

1. Introduction

The advance of additive manufacture (AM) techniques such as solid freeform fabrication (SFF) and rapid prototyping (RP) has significantly improved control over the pore network architecture of tissue engineering scaffolds [1–4]. Although tissue engineers and biomaterial scientists could to some extent solve this porous scaffold design and fabrication problem using a hybrid method which combines computer-aided design (CAD) with computer-aided manufacturing (CAM) tools, the design of the porous scaffold micro-architectures has always been one of the greatest challenges in tissue engineering. While fabrication methods such as SFF or RP have established remarkable improvements in the biomaterials and tissue engineering, there have been many problems in the design of scaffolds to meet multiple biophysical and biological requirements due to the limitations of currently available commercial CAD systems.

The problems are originated from two major sources. First, the mathematical definition of micro-architectures along with the macro-structure requires a huge memory on current CAD systems. Secondly, even if such mathematical definition can be generated using CAD systems, it would be almost impossible to transfer such detailed micro-structure information to SFF or RP machines using industry standard file formats such as STL.

Generally, STL includes approximation of surfaces with triangular facets and is therefore extremely inefficient at describing the scaffolds' micro-level pore shapes and intricate internal architectures. If the scaffold geometrical model demands more stringent precision, the number of triangular facets required to adequately approximate the scaffold model will dramatically increase. This usually results in large file sizes. Moreover, it is not uncommon to see defects or missing sections in slicing data produced largely due to the complexity in creating proper cross-sections from the STL file. Recently, Materialize Mimics™ software provided an advanced conversion module to convert 2D bitmap data (e.g. CT data) directly to the SLI format of stereolithography machine with no intermediate STL file. Although this method is not exactly the same as our method to be proposed in this work in the major aims, it is apparent that we must seek a novel interior architecture design approach to generate layered scaffold freeform fabrication tool paths without forming complicated 3D CAD scaffold models.

Recently, a group of researchers [5] already observed that the representation of micro-structural detail along with the macro-structure induces many aforementioned problems. To overcome those obstacles, they developed a tool path generation algorithm for freeform fabrication of tissue scaffolds, which enables the generation of internal scaffold patterns from characteristic unit cell building blocks. However, there were few limitations in their approach. In the method, the external surface of the scaffold was

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http://dx.doi.org/10.1016/j.medengphy.2012.05.008

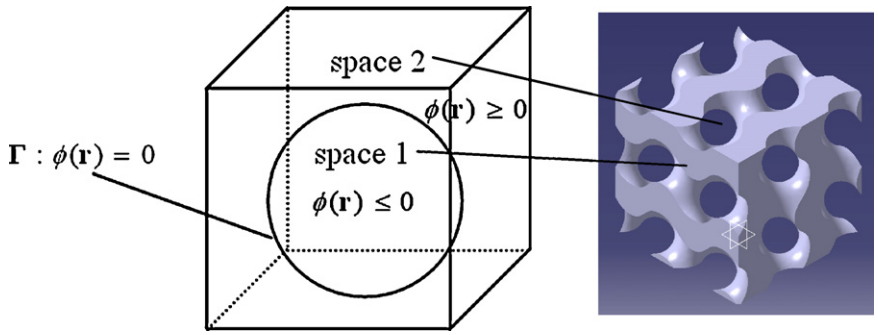

Fig. 1. Schematic diagram illustrating a TPMS that divides the unit cell into two sub-spaces [6,7].

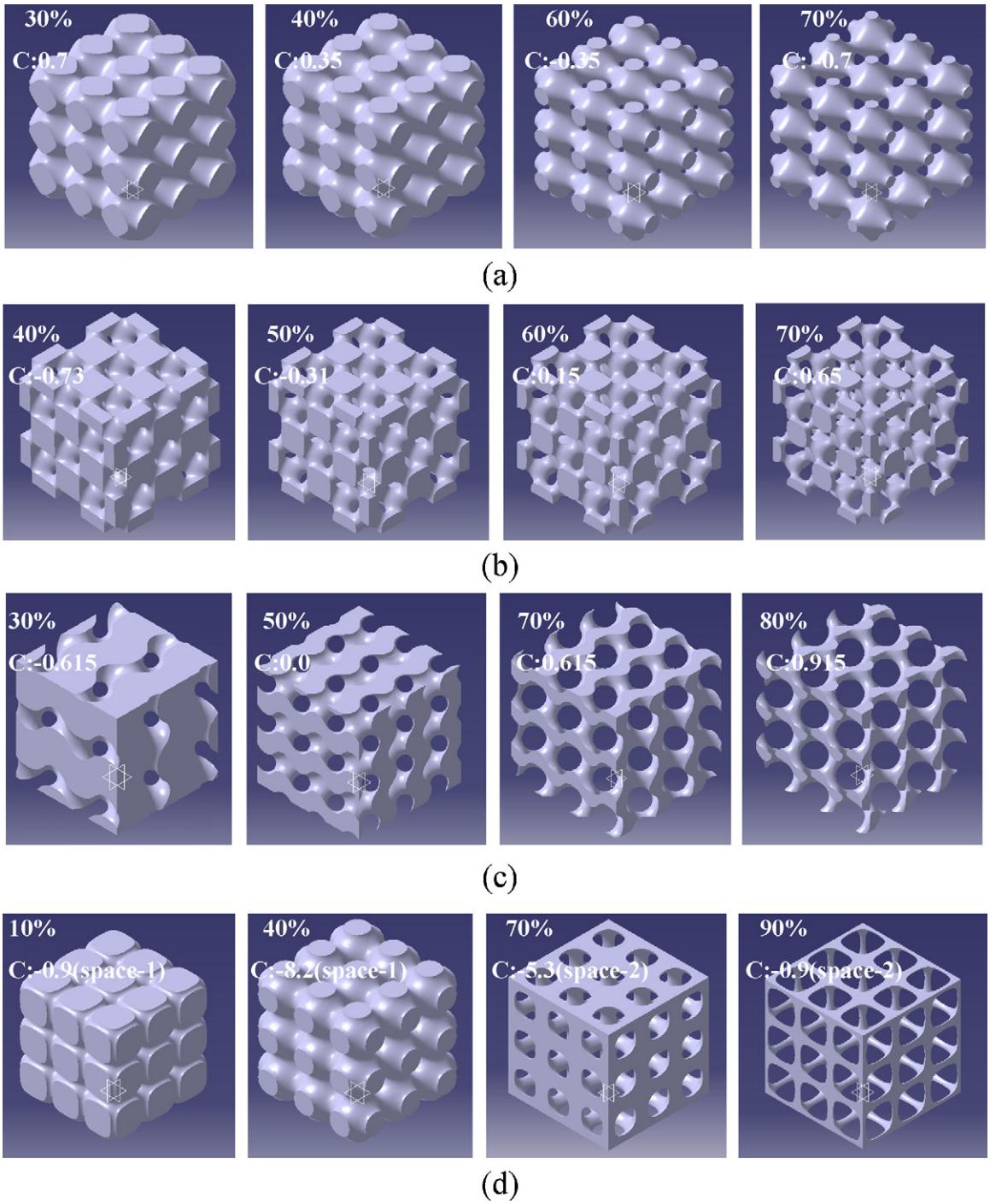

Fig. 2. A variety of TPMS-based unit cell libraries: (a) P-surface, (b) FRD-surface, (c) G-surface, (d) Tubular-P surface.