Acta Biomaterialia 8 (2012) 3138–3143

Contents lists available at SciVerse ScienceDirect

Acta Biomaterialia

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

Micromechanical finite-element modeling and experimental characterization of the compressive mechanical properties of polycaprolactone–hydroxyapatite composite scaffolds prepared by selective laser sintering for bone tissue engineering

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ARTICLE INFO

Article history:
Received 10 January 2012
Received in revised form 26 March 2012
Accepted 11 April 2012
Available online 19 April 2012

Keywords:
Polycaprolactone
Hydroxyapatite
Selective laser sintering

ABSTRACT

Bioresorbable scaffolds with mechanical properties suitable for bone tissue engineering were fabricated from polycaprolactone (PCL) and hydroxyapatite (HA) by selective laser sintering (SLS) and modeled by finite-element analysis (FEA). Both solid gage parts and scaffolds having 1-D, 2-D and 3-D orthogonal, periodic porous architectures were made with 0, 10, 20 and 30 vol.% HA. PCL:HA scaffolds manufactured by SLS had nearly full density (99%) in the designed solid regions and had excellent geometric and dimensional control. Through optimization of the SLS process, the compressive moduli for our solid gage parts and scaffolds are the highest reported in the literature for additive manufacturing. The compressive moduli of solid gage parts were 299.3, 311.2, 415.5 and 498.3 MPa for PCL:HA loading at 100:0, 90:10, 80:20 and 70:30, respectively. The compressive effective stiffness tended to increase as the loading of HA was increased and the designed porosity was lowered. In the case of the most 3-D porous scaffold, the compressive modulus more than doubled from 14.9 to 36.2 MPa when changing the material from 100:0 to 70:30 PCL:HA. A micromechanical FEA model was developed to investigate the reinforcement effect of HA loading on the compressive modulus of the bulk material. Using a first-principles based approach, the random distribution of HA particles in a solidified PCL matrix was modeled for any HA loading to predict the bulk mechanical properties of the composites. The bulk mechanical properties were also used for FEA of the scaffold geometries. The results of the FEA were found to be in good agreement with experimental mechanical testing. The development of patient- and site-specific composite tissue-engineering constructs with tailored properties can be seen as a direct extension of this work on computational design, a priori modeling of mechanical properties and direct digital manufacturing.

1. Introduction

Additive manufacturing is a promising emerging field of research for the manufacture of bioresorbable scaffolds in tissue engineering of skeletal defects. Bioresorbable scaffolds are used in bone tissue engineering to act as a controlled extracellular environment where the cells can attach, differentiate and regenerate tissue. Additive manufacturing methods enable control over the microarchitecture of the scaffold, which in turn dictates the geometry of the newly formed tissue.

Selective laser sintering (SLS) is a laser-based additive manufacturing technique in which an object is built layer-by-layer using powdered materials, radiant heaters and a computer-controlled laser [1]. In SLS, the digital representation of an object is mathematically sliced into a number of thin layers. The object is then created by scanning a laser beam and selectively fusing (melting or sintering) patterns into sequentially deposited layers of a powder. Each patterned layer of powder is also fused to its underlying layer and corresponds to a cross-section of the object as determined from the mathematical slicing operation. This layered manufacturing method allows the fabrication of scaffolds with a high degree of geometric complexity and enables the direct conversion of a scaffold's computer model into its physical realization—allowing patient-specific and tissue-specific reconstruction strategies to be easily developed [2–10].

In previous work [11], we demonstrated the ability of SLS to produce viable polycaprolactone (PCL) scaffolds for bone tissue engineering; however, the scaffolds had some manufacturing-induced porosity (20%) and only moderate geometric control. We later improved the processing parameters for the SLS of PCL and were able to produce scaffolds with nearly full density (>95%) and better geometric control (3–8%) [12]. Recently, we showed that parts manufactured by SLS with optimized processing parameters could have properties matching those made by conventional techniques such as injection or compression molding, and that

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1742-7061/$ - see front matter
http://dx.doi.org/10.1016/j.actbio.2012.04.022