Mechanics of Materials 94 (2016) 26–37

Contents lists available at ScienceDirect

Mechanics of Materials

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

Design, manufacture and tensile properties of stochastic porous metallic structures

C. Simoneau, V. Brailovski, P. Terriault*

Ecole de technologie superieure, Department of Mechanical Engineering, 1100 Notre-Dame Street West, Montreal, Quebec H3C1K3, Canada

ARTICLE INFO

Article history:
Received 19 June 2015
Revised 9 November 2015
Available online 2 December 2015

Keywords:
Stochastic porous open-cell structures
Additive manufacturing
Porosity gradient
Medical applications
Representative Volume Element
Finite Element Analysis

ABSTRACT

An original methodology was proposed to design, manufacture and test stochastic porous open-cell structures for medical applications. The first phase of the design procedure consisted in the numerical determination of the minimum representative size of the porous gauge section of testing specimens. Next, porosity gradients between the porous gauge section and the fully dense grip extremities of the specimens were created. The tensile specimens with porosities of 0.30, 0.40 and 0.50 were then produced using cobalt–chromium alloy powders and the Selective Laser Melting (SLM) technology. Finally, the specimens were subjected to uniaxial tension to failure to allow the determination of their stiffness and mechanical strength. The elastic response of these specimens in the central gauge section and the porosity gradient zones were in line with our numerical predictions and the literature data.

1. Introduction

In orthopedics, porous metals can be advantageously used for the replacement of damaged bones. To maximize the immediate and long-term success of orthopedic surgery, porous implants must fulfill specific biological and mechanical requirements. While biocompatibility and corrosion resistance are essential from a biological viewpoint (Lefebvre, 2013), it has been shown that a specific pore size range (50–800 μm) and an open-cell structure are two essential factors for a successful bone ingrowth (Bobyn et al., 1980). Furthermore, since the stiffness of porous implants can be adjusted to match that of bone, a stiffness mismatch between the implant and bone can be reduced, along with the risks of bone resorption and implant loosening. In addition to the mechanically biocompatible Young's modulus, the strength of porous implants must be higher than that of bone to prevent implant failure.

Generally speaking, the morphology of porous materials can be classified into two groups: stochastic (random) and ordered (regular, unit-cell), and it represents a fundamental aspect to take into account since it strongly impacts biomechanical compatibility requirements.

Despite the marked tendency to produce ordered structures for biomedical applications (see Campoli et al., 2013; Cansizoglu et al., 2008; Horn et al., 2014), numerous authors (Alkhader and Vural, 2008; Roberts and Garboczi, 2002; Sotomayor and Tippur, 2014; Tang et al., 2014) have raised the concern that these regular morphologies significantly differ from those of load-bearing natural cellular materials with strongly irregular interconnected-cell architectures. Moreover, Alkhader and Vural (2008) mentioned that random foams are more likely to have isotropic properties, as compared to the majority of regular lattice structures exhibiting a strong anisotropy. Random foam structures should therefore be favored over regular foams for such applications.

Two groups of manufacturing technologies are largely used to produce stochastic foams: (a) polymer-foam replication using deposition or infiltration-sintering techniques (Bobyn et al., 1999; Ryan et al., 2008), and (b) fugitive foaming or passive space-holder powder metallurgy techniques (Gauthier et al., 2004; Rivard et al., 2014). These

* Corresponding author. Tel.: +1 514 396 8518.
E-mail address: patrick.terriault@etsmtl.ca (P. Terriault).

http://dx.doi.org/10.1016/j.mechmat.2015.11.010
0167-6636/

methods have been widely reviewed by Banhart (2001), Baumeister and Weise (2013) and many others. However, over the last two decades, additive manufacturing (AM) technologies have drawn the attention of the scientific community due to their capacity to produce complex customized parts and enable design optimization to meet specific application requirements.

Compared to traditional subtractive or formative manufacturing processes, AM technologies build near-net-shape parts directly from three-dimensional (3D) CAD models. Such a straightforward approach results in reduced energy consumption, carbon footprint, production time and cost (Frazier, 2014). In the biomedical domain, metal AM technologies are of particular interest since they can be used to create patient-specific implants which would exhibit porous morphology to promote bone ingrowth and therefore, solid fixation of the implant (Murr et al., 2011). Conventional subtractive or formative manufacturing processes can hardly combine these two advantages.

Although only a limited number of studies have so far been conducted on the AM-built stochastic open-cell metal foams, it is however possible to come up with a few. Among them, Cheng et al. (2014) and Murr et al. (2010) successfully used computed tomography (CT), electron beam melting (EBM) AM technology and Ti–6Al–4V powder to replicate a biomimetic hip stem composed of an 81% porosity cylindrical core surrounded by a 76% porosity shell (Murr et al., 2010), and the structure of a human femoral head (Cheng et al., 2014).

The advantages of producing stochastic foams for orthopedic implants using AM technologies being demonstrated, this paper focuses on the development of an original methodology for the design, manufacture and mechanical characterization of stochastic open-cell porous structures. Contrary to the majority of studies, in which these structures are characterized in compression, we orient our work toward their tensile characterization to prevent certain artifacts related to foam compression, such as cell densification or friction on the interface between the specimen and the platens of the testing machine. Moreover, the foam stiffness (E) and yield stress (S_Y) are identical when they are characterized in compression and in tension (Gibson and Ashby, 1999), and these two metrics are the most important mechanical properties to consider when developing load-bearing implant materials.

To reach this objective, a multiscale modeling approach and the random porosity morphology generation algorithm are used in this study (Section 2.1). The developed methodology is then presented in Section 2.2 through a step-by-step procedure. Next, Section 2.3 presents the determination of a minimum (or representative) size of the numerically-generated foams through finite elements-based simulations. This is followed by the design of tensile specimens with porosity gradients to allow an adequate connection between the porous gauge section and the fully dense grip extremities. The manufacture of these porous specimens using selective laser melting (SLM) AM technology is then presented in Section 2.4, while Section 2.5 is dedicated to the tensile characterization of the specimens. Finally, Sections 3 and 4 present the results and discussion, respectively.

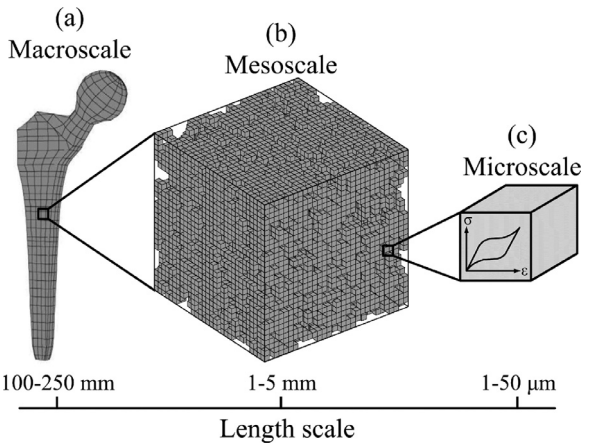

Fig. 1. Schematization of the multiscale modeling approach adapted from Simoneau et al. (2014).

2. Methodology of design, manufacture and testing of stochastic porous structures

2.1. Presentation of the multiscale modeling approach

The design procedure adopted in our work is based on a multiscale modeling approach involving a combination of micro-, meso- and macroscale models (Fig. 1). Such an approach was adopted in our previous papers (Maître jean et al., 2013; Simoneau et al., 2014) considering the tremendous numerical cost associated with a direct finite element (FE) modeling of porous implant structures. A "macroscale" model is intended to simulate the global behavior of the implant. This model is homogeneous and makes abstraction of a complex structural organization of the implant. The mechanical properties of the macroscale model are equivalent to those of the porous material, and they are obtained with a "mesoscale" model. The morphology of the latter represents an assembly of interconnected matter voxels (or volumetric pixels) comprised within a cubic domain, called a Representative Volume Element (RVE). Finally, each finite element of an RVE is driven by a "microscale" model governed by the constitutive relations of a bulk (solid) material.

In this work, parallels can be drawn between each of the three modeling scales (macro-, meso-, and micro-) and a physical object, which in our case, is a tensile specimen. The macro- and mesoscale models are respectively associated with the tensile specimen as a whole, and with its Representative Volume Element (i.e., gauge section). The microscale model simulates the behavior of every matter voxel linked to the stress–strain diagram obtained through the testing of an entirely dense specimen produced from the same material (cobalt–chromium alloy) and by the same method (SLM) as its porous counterparts.

RVEs are created using an original morphology generation algorithm in the MATLAB 2013b environment (MathWorks, Natick, MA, USA) controlled by two parameters: the size of the cubic domain (S_{RVE}) and the pore volume fraction (PVF) (see Fig. 2 for three different S_{RVE} − PVF combinations and refer to Simoneau et al. (2014) for details). This algorithm was developed in part to eliminate the need of using a