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Research Paper

Mechanical behavior of regular open-cell porous biomaterials made of diamond lattice unit cells

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ABSTRACT

Cellular structures with highly controlled micro-architectures are promising materials for orthopedic applications that require bone-substituting biomaterials or implants. The availability of additive manufacturing techniques has enabled manufacturing of biomaterials made of one or multiple types of unit cells. The diamond lattice unit cell is one of the relatively new types of unit cells that are used in manufacturing of regular porous biomaterials. As opposed to many other types of unit cells, there is currently no analytical solution that could be used for prediction of the mechanical properties of cellular structures made of the diamond lattice unit cells. In this paper, we present new analytical solutions and closed-form relationships for predicting the elastic modulus, Poisson's ratio, critical buckling load, and yield (plateau) stress of cellular structures made of the diamond lattice unit cell. The mechanical properties predicted using the analytical solutions are compared with those obtained using finite element models. A number of solid and porous titanium (Ti6Al4V) specimens were manufactured using selective laser melting. A series of experiments were then performed to determine the mechanical properties of the matrix material and cellular structures. The experimentally measured mechanical properties were compared with those obtained using analytical solutions and finite element (FE) models. It has been shown that, for small apparent density values, the mechanical properties obtained using analytical and numerical solutions are in agreement with each other and with experimental observations. The properties estimated using an analytical solution based on the Euler–Bernoulli theory markedly deviated from experimental results for large

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apparent density values. The mechanical properties estimated using FE models and another analytical solution based on the Timoshenko beam theory better matched the experimental observations.

1. Introduction

Cellular structures possess certain combinations of geometrical features, mechanical properties, and physical properties (Thiyagasundaram et al., 2010) that make them suitable for many applications in industry as well as in medicine. One of the most important applications of cellular solids is in orthopedic surgery where orthopedic implants are needed to replace bone and integrate with the host bony tissue (Kujala et al., 2003; Mullen et al., 2009; Van der Stok et al., 2012, 2013). In such applications, a biomaterial is needed that has mechanical properties similar to that of the bone it replaces. Moreover, the biomaterial should be biocompatible, allow for bone ingrowth and optimal osseointegration, and have the ability to deliver therapeutic agents.

Partly because of their high porosity and huge surface to volume ratio, cellular metallic biomaterials such as cellular titanium alloys satisfy all the above-mentioned criteria. For example, the elastic properties of porous titanium are shown to be similar to that of bone (Amin Yavari et al., 2013; Campoli et al., 2013a; Greiner et al., 2005; Oh et al., 2003; Wen et al., 2002). Moreover, titanium alloys are biocompatible and corrosion resistant (Long and Rack, 1998). Porous titanium is also shown to allow for bone ingrowth and osseointegration (Pilliar, 1983; Van der Stok et al., 2012). Finally, the ample pore space and large surface area of porous biomaterials have been used for delivery of therapeutic agents such as growth factors (Jansen et al., 2005; Van der Stok et al., 2013).

Cellular structures such as cellular biomaterials are made of either two-dimensional unit cells such as honeycombs (Gibson et al., 1982; Li et al., 2010) or are based on three-dimensional unit cells such as tetradecahedron (Kelvin unit cell) (Jang et al., 2008; Lalvani, 2011; Roberts and Garboczi, 2002; Sullivan et al., 2008), rhombic dodecahedron (Babaee et al., 2012), cubic (Parthasarathy et al., 2011, 2010), or diamond lattice (Campoli et al., 2013b; Heinl et al., 2008a). The type of the unit cell and its dimensions are shown to determine the mechanical properties of the cellular structure (Campoli et al., 2013a; Gibson and Ashby, 1999; Li et al., 2004). It is therefore important to study how the mechanical properties of cellular biomaterials change with the type and dimensions of the unit cell.

Many of the above-mentioned unit cells have been extensively studied before, and analytical relationships are presented for prediction of the mechanical properties of cellular structures made of those unit cells. The availability of additive manufacturing techniques such as selective laser melting (Barbas et al., 2012; Kruth et al., 2005; Lin et al., 2007; Warnke et al., 2008), selective laser sintering (Traini et al., 2008; Williams et al., 2005), and selective electron beam melting (Hrabe et al., 2011) has enabled manufacturing of porous structures based on any arbitrary type of unit cells including a number of relatively new unit cells.

The mechanical properties and permeability of cellular structures are dependent on their morphological features such as the type of unit cell, porosity, and pore size (Heinl et al., 2008b; Truscello et al., 2012). The biological performance of cellular structures such as cell attachment, growth, and differentiation are also dependent on the pore shape, pore size, and porosity (Van Bael et al., 2012). It is therefore important to study the mechanical properties, fluid flow properties, and biological performance of a wide range of unit cells in order to generate a library of different unit cell types that could be used for optimal design of implants and tissue engineering scaffolds. The diamond lattice unit cell is one of the relatively new types of unit cells that have not been extensively studied before. In an experimental study, the mechanical properties of a specific deign of the diamond-type cellular structures (Ti–6Al–4V alloy, selective electron beam melting) were found to be close to those of trabecular bone (Heinl et al., 2008b). However, there are currently no analytical relationships for predicting the mechanical properties of cellular structures made of the diamond unit cell.

In this paper, we study the mechanical properties of cellular titanium solids made of diamond unit cells. First, analytical solutions are presented that could predict the mechanical properties of the diamond-type cellular solids including their Young's modulus, Poisson's ratio, yield stress, and critical buckling load. Then, a finite element model is used for estimating the mechanical properties of the diamond-type cellular solids. Finally, the mechanical behavior of selective laser melted porous titanium structures made of the diamond lattice unit cell is studied experimentally. The results of the presented analytical solutions, finite element model, and experimental study are compared with each other to study the ability of analytical and numerical solutions in capturing the experimentally observed mechanical behavior.

2. Materials and methods

2.1. Analytical model

Diamond cubic unit cell is an isotropic geometry that has fourteen vertices and sixteen equal edges (Fig. 1). Each node is connected to four other nodes and the angle between every two struts is 109.5°. The length of each strut (L), length of the unit cell (a), and the angle between struts and the horizontal plane, θ, are related to each other through the following relationships:

$$a = 2\sqrt{2}\,L\cos\theta,\quad a = \frac{4\sqrt{3}}{3}L,\quad \theta = 35.26^{\circ} \tag{1}$$