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Research Paper

Relationship between unit cell type and porosity and the fatigue behavior of selective laser melted meta-biomaterials

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ABSTRACT

Meta-materials are structures when their small-scale properties are considered, but behave as materials when their homogenized macroscopic properties are studied. There is an intimate relationship between the design of the small-scale structure and the homogenized properties of such materials. In this article, we studied that relationship for meta-biomaterials that are aimed for biomedical applications, otherwise known as meta-biomaterials. Selective laser melted porous titanium (Ti6Al4V ELI) structures were manufactured based on three different types of repeating unit cells, namely cube, diamond, and truncated cuboctahedron, and with different porosities. The morphological features, static mechanical properties, and fatigue behavior of the porous biomaterials were studied with a focus on their fatigue behavior. It was observed that, in addition to static mechanical properties, the fatigue properties of the porous biomaterials are highly dependent on the type of unit cell as well as on porosity. None of the porous structures based on the cube unit cell failed after 10^6 loading cycles even when the applied stress reached 80% of their yield strengths. For both other unit cells, higher porosities resulted in shorter fatigue lives for the same level of applied stress. When normalized with respect to their yield stresses, the S-N data points of structures with different porosities very well ($R^2>0.8$) conformed to one single power law specific to the type of the unit cell. For the same level of normalized applied stress, the truncated cuboctahedron unit cell resulted in a longer fatigue life as compared to the diamond unit cell. In a similar comparison, the fatigue lives of the porous structures based on both truncated cuboctahedron and diamond unit cells were longer than that of the porous structures based on the rhombic dodecahedron unit cell

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(determined in a previous study). The data presented in this study could serve as a basis for design of porous biomaterials as well as for corroboration of relevant analytical and computational models.

1. Introduction

Recent advances in additive manufacturing as well as in other multi-scale manufacturing techniques have enabled production of very complex structures with high precision and controllability down to micrometer scale (Cohen et al., 2010; Dalton et al., 2013; Melchels et al., 2012; Podshivalov et al., 2013). As a consequence, a new class of materials is emerging that might be called "meta-materials" (Garcia et al., 2012; Méjica and Lantada 2013; Zhou 2013). The concept of meta-materials is an in-between concept halfway from both "materials" and "structures." A meta-material is a structure as far as its small-scale features and properties are concerned, but behaves like a material when its homogenized properties are evaluated at the large, that is, macro, scale. The rationally-designed small-scale structure of meta-materials may give rise to unprecedented or rarely observed macro-scale properties including acoustic (Christensen and de Abajo 2012; Liang and Li 2012; Park et al., 2011), dielectric (Levy et al., 2007; Schuller et al., 2007; Vynck et al., 2009; Zhao et al., 2009), and mechanical properties (Fang et al., 2006; Ju et al., Fadel). Those properties are important for application of meta-materials in different industries including the medical industry. When dealing with additively manufactured meta-materials that are aimed for biomedical applications, the more specific term of "meta-biomaterials" may be used. Although more generic terms such as porous biomaterials have been used in the past for describing this class of biomaterials, it seems important to use a more modern term such as "meta-biomaterials" to clarify the connection of this material with other types of meta-materials and distinguish them from the porous biomaterials manufactured using conventional techniques such as space-holder (Aydoğmuş and Bor, 2009; Kolk et al., 2012; Niu et al., 2009; Wang et al., 2009) and gas foaming (Harris et al., 1998; Kim et al., 2006; Salerno et al., 2009; Yoon and Park, 2001). Although conventional techniques could be used for adjusting the composition, pore shape, porosity, and mechanical properties of biomaterials (Li et al., 2009; Wen et al., 2010), they have limited potential for free-form fabrication of fully interconnected porous biomaterials based on rationally designed repeating unit cells.

One of the applications of meta-biomaterials is in bone tissue regeneration and orthopedic implants. The mechanical properties of meta-materials in general and meta-biomaterials in particular including stiffness values comparable to those of bone (Van der Stok et al., 2013), adjustable permeability (Dias et al., 2014; Lewis 2013; Truscello et al., 2012; Van Bael et al., 2012), huge surface area that could be modified for bio-functionalization (Amin Yavari et al., 2014a, 2014c; Chai et al., 2011; Heinl et al., 2008), and negative Poisson's ratio (Greaves et al., 2011) have important applications in orthopedics and skeletal tissue regeneration. However, the different properties of this type of porous biomaterials are not well understood. Of particular importance are the deformation and fracture mechanisms of the different classes of meta-biomaterials. As previously implied, the mechanical properties of meta-biomaterials are highly dependent on the design of their small-scale structure (Zhou 2013; Campoli et al., 2013; Murr et al., 2011; Parthasarathy et al., 2011). Recently, a growing number of researchers have tried to study the relationship between the geometrical design of the ultra-structure of meta-biomaterials and their mechanical properties (Campoli et al., 2013; Ahmadi et al., 2014a; Babaee et al., 2012; Li et al., 2014). However, there are very few studies (Amin Yavari et al., 2013; Hrabe et al., 2011) on the fatigue behavior of such meta-biomaterials. The aim of the current study is to contribute towards understanding the relationship between the geometrical design of meta-biomaterials at the small-scale and their fatigue properties. Selective laser melted (SLM) porous titanium structures based on three different types of space-filling unit cells including cube, diamond, and truncated cuboctahedron were considered. The relationship between the type of the unit cell and porosity on the one hand and the fatigue behavior of porous structures on the other hand is not yet well understood. In this article, we study the relationship between the geometrical design of porous structures including the type of unit cell and porosity and their fatigue behavior.

2. Materials and methods

2.1. Manufacturing techniques

An additive manufacturing technique, namely SLM, was used for production of the specimens used for morphological characterization, static mechanical testing, and fatigue experiments. The powder used for laser processing was made of Ti6Al4V- ELI according to ASTM F136 (grade 23). The other details of the manufacturing process and processing parameters have been described elsewhere (Amin Yavari et al., 2014a; Ahmadi et al., 2014a; Amin Yavari et al., 2014b). The specimens were manufactured on top of a solid titanium substrate and were subsequently removed from the substrate using Electrical Discharge Machining (EDM). All specimens were approximately 15 mm in length and 10 mm in diameter, and had an entirely porous structure based on three types of space-filling unit cells including cube, truncated cuboctahedron, and diamond unit cells (Fig. 1). Different porosities were achieved by changing the strut thickness (Table 1).