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Research Paper

Effects of bio-functionalizing surface treatments on the mechanical behavior of open porous titanium biomaterials

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ABSTRACT

Bio-functionalizing surface treatments are often applied for improving the bioactivity of biomaterials that are based on otherwise bioinert titanium alloys. When applied on highly porous titanium alloy structures intended for orthopedic bone regeneration purposes, such surface treatments could significantly change the static and fatigue properties of these structures and, thus, affect the application of the biomaterial as bone substitute. Therefore, the interplay between biofunctionalizing surface treatments and mechanical behavior needs to be controlled. In this paper, we studied the effects of two bio-functionalizing surface treatments, namely alkali–acid heat treatment (AlAcH) and acid–alkali (AcAl), on the static and fatigue properties of three different highly porous titanium alloy implants manufactured using selective laser melting. It was found that AlAcH treatment results in minimal mass loss. The static and fatigue properties of AlAcH specimens were therefore not much different from as-manufactured (AsM) specimens. In contrast, AcAl resulted in substantial mass loss and also in significantly less static and fatigue properties particularly for porous structures with the highest porosity. The ratio of the static mechanical properties of AcAl specimens to that of AsM specimen was in the range of 1.5–6. The fatigue lives of AcAl specimens were much more severely affected by the applied surface

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treatments with fatigue lives up to 23 times smaller than that of AsM specimens particularly for the porous structures with the highest porosity. In conclusion, the fatigue properties of surface treated porous titanium are dependent not only on the type of applied surface treatment but also on the porosity of the biomaterial.

1. Introduction

Porous titanium is considered a promising biomaterial for various applications in orthopedics including bone substitution (Bertheville, 2006; Habijan et al., 2013; Kujala et al., 2003; Li et al., 2007) and total joint replacement surgeries (Moroni et al., 1994; Mullen et al., 2009). Recently, there has been a growing interest in such porous metallic biomaterials, because advanced additive manufacturing techniques such as selective laser melting have enabled production of highly porous metallic structures (porosity$>$80%) with precisely controlled micro-architectures (Heinl et al., 2008a, 2008b; Laptev et al., 2004; Murr et al., 2010; Parthasarathy et al., 2010). The ability to manufacture highly porous titanium with arbitrary micro-architectures presents many opportunities for the design of orthopedic biomaterials. First, it is now possible to manufacture porous titanium with mechanical properties in the range of the mechanical properties of bone and below (Campoli et al., 2013; Imwinkelried, 2007; Van Noort, 1987). Second, one could combine different porous micro-architectures to optimize the distribution of mechanical properties within orthopedic implants. Third, patient-specific implants can be manufactured using additive manufacturing techniques (Giannatsis and Dedoussis, 2009; Melchels et al., 2012; Murr et al., 2011; Parthasarathy et al., 2011). Fourth, the abundance of pore space allows excessive bone ingrowth while the pore space could also be filled with drug delivery media such as gels for controlled release of growth factors (Van der Stok et al., 2013; Wang et al., 2011). Finally, open porous biomaterials have large surface area that could be modified using bio-functionalizing surface treatment techniques for improved performance of the implant.

Chemical surface modifications have been shown to effectively bio-functionalize the surface of titanium and titanium alloys (Liu et al., 2004; Rupp et al., 2006; Tan and Saltzman, 2004; Tavangar et al., 2011; Turkan and Guden, 2010a, 2010b; Variola et al., 2011, 2009, 2008; Xiong et al., 2008; Yang et al., 2004; Zhao et al., 2006, 2005). Two important chemical surface treatments, namely acid–alkali (AcAl) and alkali–acid-heat (AlAcH) treatments are often used for bio-functionalizing purposes of Ti alloys. As explained below, the bio-functionalizing effects of both surface treatments can be attributed to the micro-topography that they create as well as their resulting surface chemistry. As for the micro-topography, it has been shown that the small-scale features created by AcAl and AlAcH surface modifications could increase bone regeneration (Balasundaram and Webster, 2006; Dohan Ehrenfest et al., 2010). The surface chemistry of AcAl and AlAcH treatments work differently. In the AcAl treatment, the acidic treatment removes the passive oxide layer, while the alkali treatment creates an amorphous sodium titanate layer (Zhao et al., 2010b). The release of Na^+ ion from the sodium titanate layer could contribute to formation of Ti-OH groups that facilitate formation of bone-like apatite (Zhao et al., 2010a). In the AlAcH treatment, the alkali treatment creates a sodium titanate layer (Zhao et al., 2010b). Then, the acidic treatment removes sodium and contributes to the formation of an amorphous titania (Takemoto et al., 2006). The subsequent heat treatment transforms the amorphous titania to crystalline titania (anatase and/or rutile) (Takemoto et al., 2006) that is beneficial for the formation of apatite due to a proper atomic arrangement of the crystalline structure (Narayanan et al., 2008).

Even though surface modifications have been shown to affect bio-functionalizing and improve the interaction of the implant surface with the host tissue, they might also have consequences in terms of the mechanical properties, especially for open porous implants that have a completely different surface to volume ratio as compared to dense Ti implants. Since chemical surface treatment of open porous structures is often associated with strut erosion and creates micro-features on the surface, it is not clear how the static and dynamic mechanical properties of the porous structure change after such modifications. The modifications might be particularly detrimental to the fatigue properties of porous structures, as these complex geometrical constructs are generally more sensitive to notches and stress concentration sites due to their high surface to volume ratio.

In this paper, we studied the effects of AlAcH and AcAl chemical surface modifications on the static and dynamic mechanical properties of porous titanium structures for three different porosities. In particular, we studied how the mechanical properties of the porous structures change as compared to as-manufactured materials. The porous structures were scanned using micro-CT and the images were analyzed to determine the morphological parameters of the porous structures. The porous structures were subsequently subjected to static and dynamic mechanical testing. A statistical analysis was performed to determine whether the static and fatigue properties of the surface-treated structures are significantly different from those of as-manufactured structures.

2. Materials and methods

2.1. Materials and manufacturing

An additive manufacturing technique, namely selective laser melting (Layerwise NV, Belgium), was used for manufacturing open porous titanium alloy structures based on a dodecahedron unit cell (Fig. 1a). Cylindrical specimens with