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Research Paper

Compensation strategy to reduce geometry and mechanics mismatches in porous biomaterials built with Selective Laser Melting

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The accuracy of Additive Manufacturing processes in fabricating porous biomaterials is currently limited by their capacity to render pore morphology that precisely matches its design. In a porous biomaterial, a geometric mismatch can result in pore occlusion and strut thinning, drawbacks that can inherently compromise bone ingrowth and severely impact mechanical performance. This paper focuses on Selective Laser Melting of porous microarchitecture and proposes a compensation scheme that reduces the morphology mismatch between as-designed and as-manufactured geometry, in particular that of the pore. A spider web analog is introduced, built out of Ti–6Al–4V powder via SLM, and morphologically characterized. Results from error analysis of strut thickness are used to generate thickness compensation relations expressed as a function of the angle each strut formed with the build plane. The scheme is applied to fabricate a set of three-dimensional porous biomaterials, which are morphologically and mechanically characterized via micro Computed Tomography, mechanically tested and numerically analyzed. For strut thickness, the results show the largest mismatch (60% from the design) occurring for horizontal members, reduces to 3.1% upon application of the compensation. Similar improvement is observed also for the mechanical properties, a factor that further corroborates the merit of the design-oriented scheme here introduced.

1. Introduction

Additive processes provide an exciting opportunity to build metals with customized porous architecture and mechanical properties unachievable in monolithic materials (Ashby and Bréchet, 2003; Fleck et al., 2010; Schaedler et al., 2011). Porous biomaterials with tailored cell morphology enable cell proliferation and differentiation, required for bone ingrowth, as well as nutrient, oxygen and waste diffusion (Hutmacher, 2000; Yang et al., 2001; Sanz-Herrera et al., 2008). Furthermore, their

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mechanical properties can be tuned to provide adequate strength and matched stiffness with respect to anatomical location (Hutmacher, 2000; Yang et al., 2001; Sanz-Herrera et al., 2008; Arabnejad Khanoki and Pasini, 2012, 2013a, 2013b). The functionality and overall success of porous biomaterials and implants depend upon a multitude of factors including pore morphology and interconnectivity, as well as their ability to fill bone defects (Hollister and Murphy, 2011; Wu et al., 2014). Conventional manufacturing methods for open-cell porous materials, such as solid state processing (sintering of fibers and powder metallurgy), liquid state processing (spray foaming, direct foaming), vapor deposition, and electro-deposition, often fail to produce porous implants with desired porosity and homogenous distribution of pores for sufficient bone ingrowth (Ryan et al., 2006; Banhart, 2001). As an alternative, Additive Manufacturing (AM) processes, such as Electron Beam Melting (EBM) and Selective Laser Melting (SLM), are layer-by-layer technology enabling custom porous implants with internal architecture (Murr et al., 2010; Van Bael et al., 2011; Williams et al., 2005; Pattanayak et al., 2011; Heinl et al., 2008; Parthasarathy et al., 2010) and mechanical response tuned to those of the surrounding bone tissue, and pore morphology tailored to ease bone ingrowth (Sobral et al., 2011; Khoda et al., 2010).

Although AM allows control of pore architecture, current technologies fail short in reproducing cellular geometry at the expected level of fidelity and accuracy. Geometry discrepancies often appear between the as-designed and as-manufactured pore geometry, especially for architecture with element size reaching the manufacturing limits (Parthasarathy et al., 2010; Arabnejad et al., 2016a; Yan et al., 2012). The problem is serious not only because a geometry mismatch can result in pore occlusion, which in turn impair osseointegration, but also because the resulting mechanical properties can be far off from the expected values (Parthasarathy et al., 2010; Arabnejad et al., 2016a; Yan et al., 2012; Hollander et al., 2006; Mullen et al., 2010).

Previous studies have shown that strut thickness, strut cross section, strut straightness, and pore size are among the variables that most suffer from AM inaccuracy (Parthasarathy et al., 2010; Arabnejad et al., 2016a; Yan et al., 2012; Hollander et al., 2006; Mullen et al., 2010). In particular, strut thickness has been shown to be highly dependent on the angle a strut forms with the build plane. Well documented in the literature, this deviation is attributed to a difference in heat transfer properties between solid struts and their surrounding powder. For example, Gebhardt et al. (2014) reported severe stair-climbing effect for struts at 45° angle from the build plane with noticeable amount of adherent particles for struts at 90°. Several methods have been proposed to reduce the error inherent to the manufacturing process. They can be categorized in either design-oriented (Dias et al., 2014), or process-control strategies, which involve machine parameter tuning (Eshraghi and Das, 2010; Partee et al., 2005) and post-processing, such as electro polishing and acid etching (Pyka et al., 2012).

This paper introduces a design scheme to reduce fabrication deviations appearing in Ti–6Al–4V porous biomaterials built with SLM. A statistically meaningful set of spider-webs were designed with struts built at varying build angles, built with prescribed in-plane strut thickness, which in turn were measured via light microscopy. Exponential interpolation functions of the relative error appearing from the designed thickness were correlated to the build plane angle. These relations are at the core of compensation relations that enable the generation of compensated geometries that are built with higher accuracy. The scheme was experimentally validated on a spider web analog, and then applied to a set of three-dimensional porous biomaterials. Micro-CT morphological characterization, as well as mechanical property analysis conducted on compensated and uncompensated geometries, demonstrated the merit of the procedure here introduced.

2. Compensation strategy

Additive processes of metallic lattices often result in fabricated pores which contain deviations from their as-designed geometry. Fig. 1 illustrates the unit cell of a typical lattice built with SLM, where the comparison of *as-manufactured* and *as-designed* geometry points out several morphological mismatches, including formation of parasitic mass at the joints, staircase effect of diagonal struts and strut thickness heterogeneity. With respect to the latter, the figure shows that

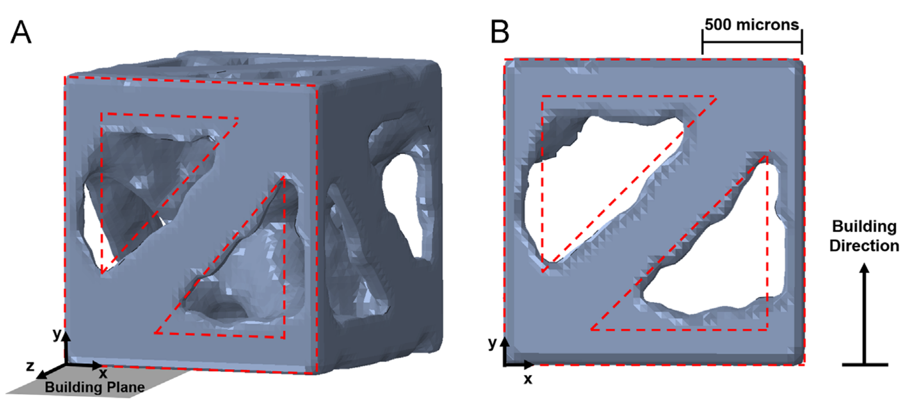

Fig. 1 – Three-dimensional reconstructed geometry of a SLM manufactured tetrahedron-based unit cell. A. Isometric view. B. Front view. Hidden lines (red) specify the ideal as-designed geometry of the unit cell. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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