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Mechanics of additively manufactured biomaterials

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ABSTRACT

Additive manufacturing (3D printing) has found many applications in healthcare including fabrication of biomaterials as well as bioprinting of tissues and organs. Additively manufactured (AM) biomaterials may possess arbitrarily complex micro-architectures that give rise to novel mechanical, physical, and biological properties. The mechanical behavior of such porous biomaterials including their quasi-static mechanical properties and fatigue resistance is not yet well understood. It is particularly important to understand the relationship between the designed micro-architecture (topology) and the resulting mechanical properties. The current special issue is dedicated to understanding the mechanical behavior of AM biomaterials. Although various types of AM biomaterials are represented in the special issue, the primary focus is on AM porous metallic biomaterials. As a prelude to this special issue, this editorial reviews some of the latest findings in the mechanical behavior of AM porous metallic biomaterials so as to describe the current state-of-the-art and set the stage for the other studies appearing in the issue. Some areas that are important for future research are also briefly mentioned.

1. Introduction

Additive manufacturing (AM) has emerged as a powerful technique for fabrication of biomaterials, tissues, and organs (Zadpoor and Malda, 2017). The free-form nature of AM offers several possibilities for design and manufacturing of biomaterials and medical devices. For example, medical devices can be designed and fabricated to exactly match the anatomy of the patients. Moreover, AM makes it possible to develop medical devices with complex shapes and multiple materials that cannot be easily manufactured using conventional techniques.

Most importantly, however, AM adds a new chapter to several decades of effort in development of biomaterials with specific mechanical, physical, or biological properties. The focus of most biomaterials research in the previous decades has been development of new materials such as new polymers, metallic alloys, or ceramics that present novel properties, which are beneficial for their intended biological function. A powerful consequence of the free-form nature of AM is that it enables obtaining completely new set of properties using the currently available biomaterials and simply through a so-called 'designer biomaterials' approach. In this approach, the properties of the biomaterial are, in addition to the properties of the bulk materials that are they made of, originating from the design of their micro-architecture and spatial arrangement of multiple biomaterials. This has close connections with the concept of meta-materials (Florijn et al., 2014; Lee et al., 2012; Shalaev, 2007; Smith et al., 2004; Zheng et al., 2014) where the physical properties of materials are originating from the ultrastructure of the material (Fig. 1).

Given the possibility of obtaining novel properties through such a 'designer biomaterial' approach, the relationship between the design of AM biomaterials including the different micro-architectural designs (Fig. 2) and the different spatial distributions of multiple biomaterials on the one hand and the resulting properties on the other have received much attention recently.

The mechanical properties of AM materials are among the most important properties of AM biomaterials that could be adjusted through the above-mentioned approaches. Last few years have seen a rapid growth of studies that address the problem of design-property relationships specifically for the quasi-static (Fig. 2a) and fatigue resistance of biomaterials (Fig. 2b). The current special issue presents a number of such studies on the mechanical behavior of AM biomaterials. As a prelude to the issue, this editorial sketches the current research landscape on the mechanical behavior of AM biomaterials and summarizes some of the most important findings reported in this special issue as well as in a number of other studies. Even though different types of biomaterials have been covered in the special issue (see e.g. Bootsma et al. (2017) and Zhou et al. (2017)), the emphasis is on AM porous metallic biomaterials (see e.g. Speirs et al. (2017) and Van Hooreweder et al. (2017)). The editorial will therefore focus primarily on such materials.

The mechanical behavior of AM porous metallic biomaterials has been systematically studied during the last few years. Porous biomaterials based on titanium and its alloys (Cheng et al., 2014; Heinl et al., 2008; Parthasarathy et al., 2010) have received the most attention, while other types of porous metallic biomaterials based on cobalt chromium (Hedberg et al., 2014; Xiang et al., 2012; Xin et al., 2013), tantalum (Wauthle et al., 2015), and stainless steel (Hao et al., 2009; Lin et al., 2007) have been studied as well. The bio-inert nature of such metallic biomaterials together with the

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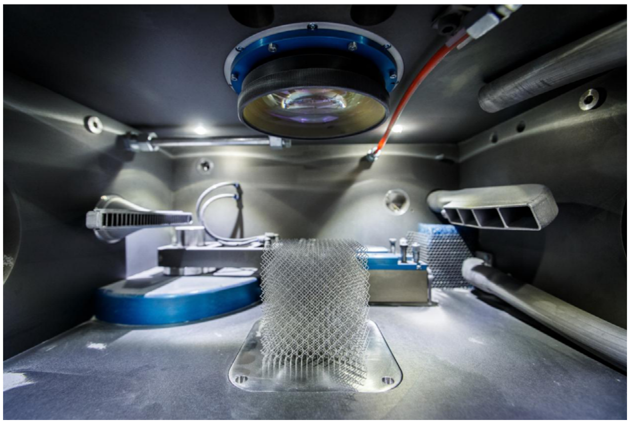

Fig. 1. An example of a penta-mode mechanical metamaterial manufactured using selective laser melting at the Additive Manufacturing Laboratory, TU Delft (Medical Delta © de Beeldredacteur).

relatively simple mechanical behavior of metallic materials (e.g. absence of strong viscoelastic behavior) creates the perfect setting to study the relationship between the topology and properties of AM porous metallic biomaterials including both quasi-static mechanical properties and fatigue resistance. The biomaterials used for such studies are generally fabricated using powder bed fusion technologies including selective laser melting (Fukuda et al., 2011; Pattanayak et al., 2011; Vandenbroucke and Kruth, 2007) and electron beam melting (Hrabe et al., 2011; Murr et al., 2011; Ponader et al., 2008).

2. Mechanical properties

The quasi-static mechanical properties of AM bulk biomaterials as well as AM porous biomaterials have been extensively studied during the last few years using analytical (Zadpoor and Hedayati, 2016), computational (Lin et al., 2007; Barbas et al., 2012; Wieding et al., 2014), and experimental (Ahmadi et al., 2015; Murr et al., 2010; Wieding et al., 2012) techniques. In general, there is a power law relationship between the relative density (porosity) of AM porous biomaterials and their elastic modulus and yield stress (Zadpoor and Hedayati, 2016) (Fig. 3a-b). However, the coefficients of the power law relationship are very different from one unit cell to another such that very different mechanical properties could be obtained for the same porosity simply by changing the type of unit cell (Fig. 3a-b). This allows for freedom in the design of porous biomaterials where competing requirements such as appropriate mass transport properties (Van Bael et al., 2012) and pore size/shape should be balanced with the required mechanical properties (Zadpoor, 2015).

Even when strong metallic alloys have been used for fabrication of AM porous biomaterials, it has been possible to achieve quasi-static mechanical properties comparable to those of trabecular and cortical bone (Ahmadi et al., 2015; Cheng et al., 2012). The fact that the homogenized mechanical properties of AM porous biomaterials with different unit cell types match those of bone allows for avoiding stress shielding and stimulating bone regeneration when designing orthopedic implants and bone tissue engineering scaffolds. The effects of mechanical properties of AM porous biomaterials on bone tissue regeneration have been studied in a few studies in which *in vivo* animal models are used (Schouman et al., 2016; Van der Stok et al., 2013). It has been found that the lower mechanical properties of AM porous biomaterials as compared to corresponding solid implants result in improved bone tissue regeneration performance of biomaterials (Schouman et al., 2016). Another study that compared the bone tissue regeneration performance of two different types of AM porous metallic biomaterials with different mechanical properties did not show significantly different bone tissue regeneration performance between both porous biomaterials, although some qualitative signs of improved bone tissue regeneration performance were found for the AM porous biomaterial with lower mechanical properties (Van der Stok et al., 2013).

As bone tissue grows into the porous structure of AM biomaterials, the mechanical properties of bone-tissue complex may significantly change. The effects of *de novo* bone tissue ingrowth on the quasi-static mechanical properties of AM porous metallic

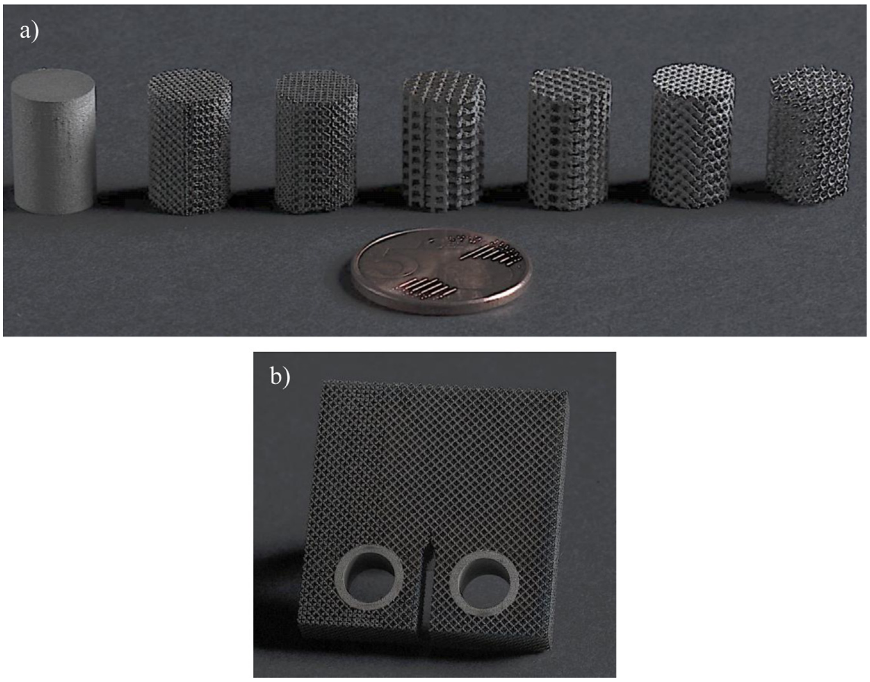

Fig. 2. Specimens with different types of micro-architectures used for quasi-static mechanical testing (similar to the ones used in Ahmadi et al. (2015)) (a), fatigue crack growth specimen made with selective laser melting from Ti-6Al-4V (b).