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Original article

Revival of pure titanium for dynamically loaded porous implants using additive manufacturing

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ABSTRACT

Additive manufacturing techniques are getting more and more established as reliable methods for producing porous metal implants thanks to the almost full geometrical and mechanical control of the designed porous biomaterial. Today, Ti6Al4V ELI is still the most widely used material for porous implants, and none or little interest goes to pure titanium for use in orthopedic or load-bearing implants. Given the special mechanical behavior of cellular structures and the material properties inherent to the additive manufacturing of metals, the aim of this study is to investigate the properties of selective laser melted pure unalloyed titanium porous structures. Therefore, the static and dynamic compressive properties of pure titanium structures are determined and compared to previously reported results for identical structures made from Ti6Al4V ELI and tantalum. The results show that porous Ti6Al4V ELI still remains the strongest material for statically loaded applications, whereas pure titanium has a mechanical behavior similar to tantalum and is the material of choice for cyclically loaded porous implants. These findings are considered to be important for future implant developments since it announces a potential revival of the use of pure titanium for additively manufactured porous implants.

1. Introduction

Porous metal structures in orthopedics were first reported in the late sixties, and ever since then the interest has only increased [1–3]. The reasons for this trend in reconstructive surgery are obvious: coming from solid metal implants with high strength and stiffness, porous metals are optimal for uncemented use since they allow for bone ingrowth through the open porosities, have an improved fixation thanks to the high roughness and corresponding coefficient of friction and have in addition a lower stiffness and thus avoid stress-shielding [4]. Today, one of the most well-known porous metal bone replacement structures is *Trabecular Metal™* (Zimmer, Warsaw, IN, USA), which is a highly porous carbon matrix coated with tantalum (Ta) [1,5–9]. But due to the high density and high cost of Ta and its difficulty to process, most orthopedic device manufacturers choose to use porous biomaterials based on titanium or titanium alloys [2,3,10]. These titanium porous structures are usually manufactured using conventional techniques such as furnace sintering, plasma spraying, lost wax casting and vapor deposition [10–13]. Recently, additive manufacturing (AM) techniques such as selective laser melting (SLM, [14]) and electron beam melting (EBM) are breaking new ground in implant manufacturing and more specifically in the manufacturing of porous metal bone replacement structures. AM allows for almost full design freedom, giving the possibility to manufacture regular open porous structures with high repeatability and thus full control over both geometrical and mechanical properties. The design freedom and reproducibility are important features when there is a need for implant performance simulations and outcome predictions [15,16]. Also, using AM has the advantage to manufacture implants with both porous and solid sections in one step (monolithic design), with less material consumption since the non-used powder can be recycled for future use, when the chemical composition is still fulfilling the required specifications and when the recycling process is free from contamination. Finally, materials like Ta that are difficult to process conventionally, could be also processed using AM, creating a whole range of new opportunities [17].

In the current study, the SLM technology was used to manufacture porous structures from commercially pure (CP) grade 1 titanium. Previous studies mostly dealt with porous structures in Ti6Al4V (grade 5 or

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grade 23), either using SLM [15,16,18–30] or EBM [13,31–36]. This biocompatible titanium alloy is the material of choice for load-bearing applications since it has a high strength to weight ratio. Commercially pure titanium (CP Ti), on the other hand, has a lower strength and therefore its use is often limited to non-load bearing applications like cranio-maxillo-facial implants [37]. A general overview of these mechanical properties of different grades of titanium and Ta can be found in Table 1.

Also, only few publications about additively manufactured CP Ti are available, all of them covering SLM of CP Ti grade 2 [41–45] and none were found that deal with CP Ti grade 1. Nevertheless, the use of CP Ti has some major advantages over alloyed titanium that can potentially bring additively manufactured CP Ti back in the scope of medical device manufacturers. First of all, CP Ti has the advantage of having no potential hazardous or toxic alloying components such as V or Al [1]. Secondly, the high ductility that provides CP Ti with the sometimes necessary deformability in certain applications like e.g. bone plates, could be an interesting property of porous metals that could be deformed intra operatively to the patient specific bone defect. And finally, in a previous study on porous Ta structures, the ductile behavior of the Ta material led to a very high fatigue strength compared to similar Ti6Al4V ELI structures and a preferential load transfer and bone ingrowth in an animal study [17]. It was proposed that the mechanical behavior of the porous Ta including its high ductility was partly responsible for the excellent *in vivo* performance of Ta. Therefore, the aim of this study is to investigate whether CP Titanium can have a revival in orthopedics as a raw material for SLM processed porous implants. This is the first study that presents and discusses the mechanical properties of additively manufactured porous structures made of CP Ti grade 1 and compares them with those of additively manufactured Ti6Al4V ELI and Ta structures. This could be useful for facilitating proper selection of the most appropriate material for the envisioned implant application.

2. Materials and Methods

The materials and methods section describes the details of the new porous CP grade 1 Ti samples, manufactured and analyzed in the current study. The properties of identical porous structures made from Ti6Al4V ELI and Ta to which the CP Ti samples will be compared were published elsewhere, unless otherwise implied [17,23].

2.1. Materials and manufacturing

Porous CP Ti grade 1 structures were manufactured from CP Ti grade 1 powder using the selective laser melting technology (3D Systems - Layerwise NV, Leuven, Belgium). The details of the laser processing method were similar to the ones presented in previous studies [19–21,23]. The unit cell used as the micro-architecture of these porous structures was in all cases dodecahedron, in four different porosities as seen on Fig. 1. This specific unit cell, pore and strut sizes were chosen in order to compare the results with those of a previous study that used identical dodecahedron structures made by SLM out of Ti6Al4V ELI powder [23]. The used nomenclature in Fig. 1 refers to the theoretical strut and pore size; e.g. Ti 120 – 500 has a theoretical strut size of 120 μm and pore size of 500 μm. In this work, spherical commercially pure grade 1 Ti powder (chemical composition according to ASTM F67, further referred to as CP Ti) with particle size ranging from 10 μm to 45 μm was used. The production was performed in an inert atmosphere and the samples were built on top of a solid Ti substrate. After production, the samples were removed from the substrate using wire electro discharge machining (EDM). Cylindrical porous specimens with a diameter of 10 mm and height of 15 mm were manufactured for morphological analysis, static and dynamic mechanical testing. The chemical composition of the porous specimens after SLM manufacturing was measured using IGA (Interstitial Gas Analysis) and ICP-OES (Inductively Coupled Plasma Optical Emission Spectrometry). With measured concentrations of C (0.0075 % wt), N (0.0100 % wt), O (0.1600 % wt), H (0.0036 % wt) and Fe (0.040 % wt), the specifications of ASTM F67 for CP Ti grade 1 are fulfilled.

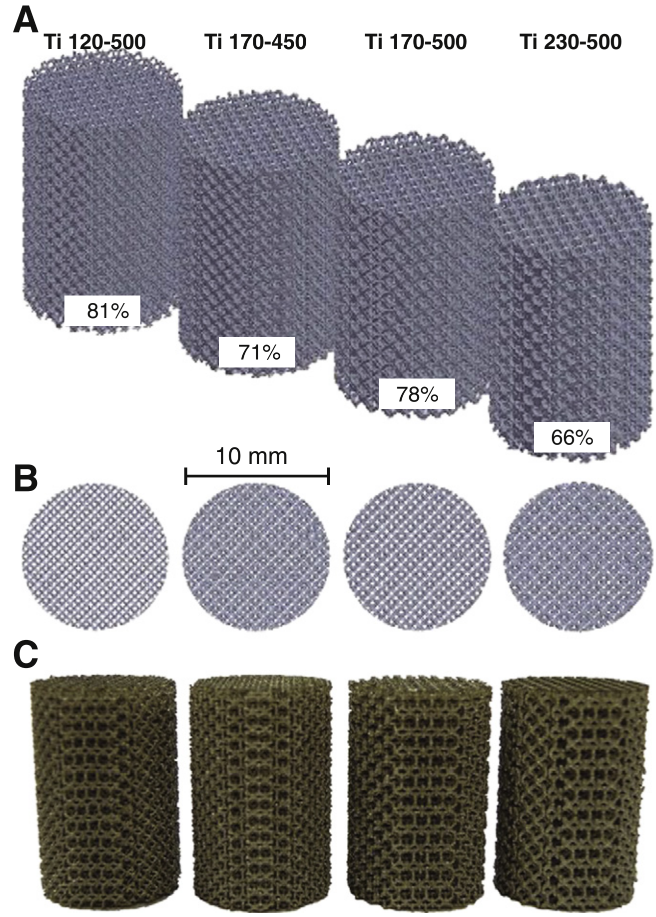

Fig. 1. Additively manufactured porous CP Ti structures: 3D CAD visual representation of the four different structures in isometric (A) and top (B) view and a picture after manufacturing (C).

Table 1
Literature values of the density and mechanical properties of standard annealed wrought titanium grades [38] and tantalum [39,40]: The density, yield strength (YS), the ultimate tensile strength (UTS), Young's modulus (E) and the elongation (e). Fatigue data are taken from [1].

Material	Density [g/cm^3]	YS [MPa]	UTS [MPa]	E [GPa]	e [%]	Fatigue [MPa]
CP Ti grade 1	4.51	170-241	240-331	103	30	270
CP Ti grade 2	4.51	280-345	340-434	103	28	330
CP Ti grade 3	4.51	380-448	450-517	103	25	350
CP Ti grade 4	4.51	480-586	550-662	104	20	376
Ti6Al4V grade 5	4.43	830-924	900-993	114	14	500
Ti6Al4V ELI grade 23	4.43	760-827	830-896	114	15	n.a.
Tantalum	16.6	165-220	200-390	186	20-50	n.a.

2.2. Morphological analysis

Overall open porosity was measured using dry weighing and Archimedes measurements on five different cylindrical samples prior to being used for mechanical testing. Dry weighing occurred under normal atmosphere conditions and overall porosity was calculated by dividing the actual weight by the theoretical weight of the macro volume using