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# Porous tantalum structures for bone implants: Fabrication, mechanical and in vitro biological properties

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ABSTRACT

The relatively high cost of manufacturing and the inability to produce modular implants have limited the acceptance of tantalum, in spite of its excellent in vitro and in vivo biocompatibility. In this article, we report how to process Ta to create net-shape porous structures with varying porosity using Laser Engineered Net Shaping (LENS™) for the first time. Porous Ta samples with relative densities between 45% and 73% have been successfully fabricated and characterized for their mechanical properties. In vitro cell materials interactions, using a human fetal osteoblast cell line, have been assessed on these porous Ta structures and compared with porous Ti control samples. The results show that the Young's modulus of porous Ta can be tailored between 1.5 and 20 GPa by changing the pore volume fraction between 27% and 55%. In vitro biocompatibility in terms of MTT assay and immunochemistry study showed excellent cellular adherence, growth and differentiation with abundant extracellular matrix formation on porous Ta structures compared to porous Ti control. These results indicate that porous Ta structures can promote enhanced/early biological fixation. The enhanced in vitro cell–material interactions on the porous Ta surface are attributed to its chemistry, its high wettability and its greater surface energy relative to porous Ti. Our results show that these laser-processed porous Ta structures can find numerous applications, particularly among older patients, for metallic implants because of their excellent bioactivity.


## 1. Introduction

Metallic biomaterials currently in use for load-bearing orthopedic applications are bioinert and lack sufficient osseointegration for implant longevity [1–3]. One consideration to improve the healing process is focused on the use of bioactive calcium phosphate ceramics on metal implants. Unfortunately, cracking, delamination and low fracture toughness of ceramic coatings still remain some of the concerns for their widespread application in load-bearing metal implants. In the last two decades, a variety of porous coatings and materials have also been used to obtain biological fixation of bone with metal implants in load-bearing implants. The most common metallic materials include sintered Ti and CoCrMo alloy beads, diffusion-bonded Ti, fiber metal and plasma-sprayed Ti [1–4]. Clinical and histological evidence from retrieved implants clearly demonstrate that these porous surfaces enhance bone tissue in-growth and are effective in supplementing the stability of the implant by biological fixation [5–7]. Table 1 reviews some of the characteristics of common porous materials pertinent to orthopedics that are commercially available. These implants can be reliably and economically manufactured and implanted in a facile and reproducible manner. However, it is also important to note that the majority of these materials are porous coatings applied on fully dense substrates. These porous materials are best suited for use as coatings since they do not have the required mechanical properties that would allow them to be used as bulk structural materials for implants, bone augmentation or substitutes for bone grafts. Moreover, these porous coated Ti alloy implants show 50–75% lower fatigue strength compared to their equivalent fully dense materials [8–10], which arises due to regions of highly concentrated stress at particle–substrate neck regions acting as crack initiation sites. Other perceived limitations of these porous metals and processing routes include: the desire for controlled porosity characteristics, the relatively high modulus of coatings, the difficulty in making stand-alone structures and the limited part geometries and sizes. Some of these limitations have been addressed by developing open cell metal structures. The overall manufacturing process involves creating a reticulated skeleton with deposition of a metal onto the surface. Trabecular Metal™ is one such open cell porous Ta marketed by Zimmer Inc. (Warsaw, IN, USA). It is made by the pyrolysis of a thermosetting polymer foam, creating a low-density vitreous carbon skeleton. Then commercially pure Ta is deposited onto this interconnected scaffold using chemical vapor deposition/infiltration [11,12]. One major limitation of these open cell porous scaffolds is lack of sufficient mechanical strength for use as load-bearing metal implants. Therefore, porous metals fabrication technologies, which can ensure a tailorable pore size, shape and distribution, net-shape fabrication capability,

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**Table 1**
Characteristics of commercial porous materials pertinent to orthopaedics.

| Name | Description | Processing | Applications | Limitations |
|---|---|---|---|---|
| Actipore™ | Fully porous NiTi alloy<br>Porosity ~ 65%<br>Pore size ~ 215 μm | Not reported | Spine and shoulder surgeries | Low mechanical properties and limited part geometries |
| Regenerex™ | Fully porous Ti<br>Porosity ~ 67%<br>Pore size ~ 300 μm<br>Modulus ~ 1.6 GPa | Porous plasma processing | Hip and shoulder surgeries | Low strength, limited sizes and only acetabular components and augments are available |
| Tritanium™ | Porous Ti coating<br>Porosity ~ 60%<br>Pore size ~ 616 μm<br>Modulus ~ 106–115 GPa | Low temperature arc vapor deposition of polyurethane foam shell | Hip surgeries | It is not manufactured as a stand-alone structure, and it is only available in acetabular components. The manufacture process is also limited at this time to large sized components |
| CSTi™ | Porous Ti coating<br>Porosity ~ 50–60%<br>Pore size ~ 400–600 μm<br>Modulus: 106–115 GPa | Powder sintering with pressure | Hip and knee surgeries | Simple and limited part geometries, low fatigue resistance |
| Stiktite™ | Porous Ti coating<br>Porosity ~ 60%<br>Pore size ~ 500 μm<br>Modulus ~ 100–110 GPa | Porous plasma processing | Hip and knee surgeries | Simple and limited part geometries, low fatigue resistance |
| Trabecular metal™ | Open cell fully porous Ta<br>Porosity ~ 75–85%<br>Pore size ~ 550 μm<br>Modulus ~ 2.5–3.9 GPa | Chemical vapor deposition/infiltration of carbon skeleton | Hip and knee surgeries | Relatively high cost of manufacture, inability to produce a modular all tantalum implant |
| CoCr beads | Porous CoCrMo coating<br>Porosity ~ 30–50%<br>Pore Size ~ 100–400 μm<br>Modulus ~ 210 GPa | Powder sintering | Hip surgeries | Simple and limited part geometries, low fatigue resistance |
| Fiber metal | Porous Ti coating<br>Porosity ~ 40–50%<br>Pore Size ~ 100–400 μm<br>Modulus ~ 106–115 GPa | Sintering | Hip surgeries | Simple and limited part geometries, low fatigue resistance |

sufficient mechanical strength and high levels of purity for biomedical applications, assume significant importance.

Among metallic biomaterials, tantalum is gaining more attention as a new biomaterial. Tantalum has been shown to be corrosion resistant [13] and bioactive in vivo [14]. Through the formation of a bone-like apatite layer in simulated body fluid, tantalum has been shown to biologically bond to bone. In several in vitro and animal studies, the porous Ta metal has provided a scaffold for bone in-growth and mechanical attachment [11,15–17]. These porous Ta components offer a low modulus of elasticity, high surface frictional characteristics and excellent osseointegration properties (i.e. bioactivity, biocompatibility and in-growth properties) [18–20]. However, the extremely high melting temperature of Ta (3017 °C), in addition to its high affinity towards oxygen, makes it difficult, if not impossible, to process Ta structures via conventional processing routes. Although Trabecular Metal™ is commercially available, the relatively high cost of manufacture and inability to produce a modular all tantalum implant has limited its widespread acceptance.

The development of porous tantalum is in its early stages of evolution, and in this work we have fabricated net shape, bulk porous Ta structures using high-power lasers in Laser Engineered Net Shaping (LENS™). The specific advantages of using laser processing in conjunction with LENS™ are: (i) the ability to control the melting of the high-melting-point Ta, thus creating fully dense or tailored porosity implants; (ii) the net-shape fabrication of complex shaped implants; (iii) the retention of a high purity of the initial power feedstock in the final product; and (iv) the production of fine and uniform microstructural features as a result of localized melting and subsequent solidification, which improve the mechanical, physical and biological properties.

In recent years, we have extensively used LENS™ to create fully dense, porous, compositionally and structurally graded materials for load-bearing metal implants [21–29]. Moreover, our recent in vitro biocompatibility study, using a human fetal osteoblast cell line (hFOB), on laser-deposited Ta coatings on Ti showed six times higher living cell density, excellent cellular adherence and growth with abundant extracellular matrix formation on the Ta coating surface compared to the Ti surface [30]. This is an important finding as such a high living cell density during in vitro biocompatibility evaluation has not been reported before for any of the currently used metallic biomaterials. Therefore, to fully utilize the excellent biocompatibility of Ta for load-bearing metal implants, suitable processing techniques have to be developed. In this context, the current article is reporting the LENS™ processing of porous Ta structures and their mechanical and in vitro biological properties.