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Low stiffness porous Ti structures for load-bearing implants

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Abstract

The need for unique mechanical and functional properties coupled with manufacturing flexibility for a wide range of metallic implant materials necessitates the use of novel design and fabrication approaches. In this work, we have demonstrated that application of proposed design concepts in combination with laser-engineered net shaping (LENS™) can significantly increase the processing flexibility of complex-shaped metallic implants with three-dimensionally interconnected, designed and functionally graded porosities down to 70 vol.%, to reduce effective stiffness for load-bearing implants. Young's modulus and 0.2% proof strength of these porous Ti samples having 35–42 vol.% porosity are found to be similar to those of human cortical bone.

Keywords: Porous titanium; Biomedical; Rapid prototyping; Laser processing; Laser-engineered net shaping (LENS™)

1. Introduction

Musculoskeletal disorders are recognized as among the most significant human health problems that exist today, costing society an estimated $254 billion every year, and afflicting one in seven Americans. In spite of the enormous magnitude of this problem, there is still a lack of bone replacement material that is appropriate for restoring lost structure and function, particularly for load-bearing applications. Traditionally, researchers have used already available materials that had been developed for aerospace or automotive applications, instead of developing new materials tailored specifically for biomedical needs. A typical example is total hip replacement (THR), in which a dense metal is used that has a significantly higher density, stiffness and strength than natural bone, which is a porous material. The typical lifetime of a THR is 7–12 years, and this lifetime has remained almost constant over the past 50 years, even though significant research and development has gone towards understanding the problem. There are three factors motivating improvements in hip joint prostheses. First, demand for implant will continue to increase due to demographic changes. The US Census estimates that the total number of people of age 65 and above will increase from 4.9 million to 39.7 million between 2000 and 2010 [1], leading to a tremendous increase in the demand for implants. Second, over the last decade, the age range has been broadened to include older patients who have greater incidence of co-morbidities. Finally, THRs are now routinely performed on younger patients, whose implants would be exposed to greater mechanical stresses for longer periods.

A summary of the physical and mechanical properties of various implant materials in comparison with natural bone is shown in Table 1. The composition of metallic implant materials is significantly different from that of natural bone. However, the necessary toughness and fatigue resistance for load-bearing implants can only be realized in metals (Table 1). As a result, the use of metallic materials for implants in load-bearing application is unavoidable. Among the various metallic biomaterials, Ti and its alloys have been recognized as desirable materials for bone implants because of their excellent corrosion resistance, biocompatibility, mechanical properties and high strength-to-weight ratio [2–6]. The first major problem concerning

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Table 1
Mechanical properties of various biomaterials used in THR (adapted from Refs. [27,42,45–47])

Material	Density ($g\ cc^{-1}$)	Compressive strength (MPa)	Elastic modulus (GPa)	Toughness ($MPa\ m^{1/2}$)	Comments
Natural bone	1.8–2.1	130–180	3–20	3–6	High strength and elastic modulus compared with nature bone leading to "stress-shielding"
Ti and Ti alloys	4.4–4.5	590–1117	55–117	55–115	
Co–Cr–Mo alloys	8.3–9.2	450–1896	200–253	100	
Stainless steels	7.9–81	170–310	189–205	50–200	
Magnesium	3.1	65–100	41–45	15–40	
High density polyethylene (HDPE)	0.94–0.96	25	1–2	–	Relatively low strength and modulus limits the use of polymers for load-bearing applications
Ultrahigh molecular weight polyethylene (UHMWPE)	0.41–0.49	28	1	20	
Polytetrafluoroethylene (PTFE)	2.1–2.3	11.7	0.4	–	
Polymethylmethacrylate (PMMA)	1.16	144	4.5	1.5	
Zirconia	6.1	2000	220	9 ($MN\ m^{-3/2}$)	Inherent brittleness and low fracture toughness
Alumina	3.98	4000–5000	380–420	3–5	
Bioglass	2.7	1000	75	–	
Hydroxyapatite (HAP)	3.1	600	73–117	0.7	
AW glass-ceramic	–	1080	118	1.9–2	

these metallic implants in orthopedic surgery is the mismatch of the Young's modulus between bone (10–30 GPa) and metallic material (110 GPa for Ti). Due to this mechanical property mismatch, bone is insufficiently loaded and becomes stress-shielded, leading to higher bone resorption. This mismatch of the Young's moduli has been identified as a major reason for implant loosening following stress shielding of bone [7–9]. Many investigators have shown that the stress-shielding retards bone remodeling and healing, which results in increased porosity in the surrounding bone [10,11]. Moreover, the moduli mismatch leads to excessive relative movement between the implant and the bone. Relative movements greater than a critical level will inhibit bone formation and ingrowth, and will result in fibrous tissue ingrowth or, in the extreme, fibrous tissue encapsulation, thereby preventing the desired implant osseointegration. The second problem with metallic implants lies in the interfacial bond between the tissue and the implant, and a weak interfacial bond due to stiffer replacement materials reduces the lifetime of the implant. An ideal implant should have the same chemistry as natural bone and similar mechanical properties, and should bond well with human tissue.

An alternative to overcome "stress-shielding" and weak interfacial bonding between the tissue and the implant is the use of porous materials. Such porous materials can reduce the stiffness mismatches and achieve stable long-term fixation due to full bone ingrowth. The rough surface morphology of the porous implant promotes bone ingrowth into the pores and provides not only anchorage for biological fixation but also a system which enables stresses to be transferred from the implant to the bone [12], leading to long-term stability [13,14]. To achieve tissue ingrowth and to attain better mechanical interlocking between implants and bone, metallic implants formed with porous surface coatings have been developed. Also, mechanical properties of porous materials can be altered and optimized by controlling porosity, pore size and shape, as well as pore distribution to suit the natural bone. A number of approaches to the fabrication of porous implants surface have been reported, including Ti powder or fibers sintering, plasma spray coating and the void–metal composite method [13,15–22]. However, porous surface implants suffer from a loss of physical properties (i.e., fatigue strength) due to stress concentrations at the porous interface and potential surface contamination from the high-temperature sintering process [15,23–25]. Wen et al. have successfully fabricated Ti foams with a porosity of 78% using a powder metallurgical process [26]. A limitation of the powder sintering approach is that pore size and shape are dictated by the powder size and shape, and are also difficult to control. Moreover, sintered metal powders are often very brittle and prone to crack propagation at low stresses, especially under fatigue conditions. Current techniques that use foaming agents, either in solid-state sintering processes or in molten metal techniques, have inherent limitations, such as contamination, presence of impurity phases, limited and predetermined part geometries, and limited control over the size, shape and distribution of the porosity. Because of these reasons, fabrication methods for porous metals that can ensure uniform pore size, shape and distribution, and high levels of purity for metals in biomedical applications are in high demand [27].

Complex-shaped porous implants cannot be fabricated using the above-cited traditional methods and the properties of the samples made are mechanically inadequate. The need for adequate mechanical and functional proper-