Effect of Porosity on Mechanical Properties and Biological Response of 3D Periodic Porous Titanium

Nikolas Hrabe[1], Russell Fernandes[1], Peter Heinl[2], Carolin Koerner[2], Raj Bordia[1].
[1]University of Washington, Seattle, WA; [2]University of Erlangen-Nuremberg, Erlangen, Germany.

Statement of Purpose: Through intentional inclusion and control of porosity in titanium, the mechanical properties can be tailored. One possible application for this material is in load-bearing orthopaedic and dental implant applications (ex. hip stems). A stiffness mismatch between the solid metal implants currently used and the surrounding bone leads to a phenomenon termed stress shielding, whereby bone remodels itself in response to the change in stress according to Wolff's law. The result is a reduction in bone density in certain areas around the implant. By increasing the amount of porosity in porous titanium, the elastic modulus can be reduced in an effort to alleviate the effects of stress shielding. If the porosity is within the optimal size range, interconnected, and open to the surface, it can also allow for post-implantation bone integration, desirably improving the bone-implant interfacial strength. To investigate the efficacy of this material in providing a more physiologically compatible implant option, elastic modulus, yield strength, fatigue strength, and in-vitro biological response were ascertained as a function of porosity. The fatigue characterization, which is a mode of implant failure, is of particular interest as there have been only a few previous studies of fatigue behavior of porous titanium.

Methods: Structures were fabricated using Arcam S12 (Molndal, Sweden) electron beam melting (EBM) equipment and Ti-6Al-4V (wt%) gas atomized powder with an average particle size of 75 µm. Structural characterization was accomplished using quantitative micro-computed x-ray tomography (microCT), scanning electron microscopy (SEM), and metallographic examination of the microstructure. Elastic modulus and yield strength were evaluated from monotonic compression tests (strain rate = 10^{-3} sec^{-1}), and compared to the Gibson-Ashby model for cellular solids [1]. Compression-compression fatigue testing (15 Hz, R = 0.1) was used to investigate the fatigue behavior of these structures. In-vitro characterization was performed over a 4-week period using human osteosarcoma cells (SAOS-2). Proliferation was measured using a cell counter, type I collagen was measured via biochemical methods, and cell morphology was observed using SEM.

Results: Interconnected pores in the optimal size range for bone integration were achieved. Structures were measured to be in the range of 66-86% porous. Metallographic examination yielded an acicular microstructure, which was expected for EBM Ti-6Al-4V. Partially sintered particles were observed to cover a majority of strut surfaces (Figure 1). Elastic moduli (0.9-6.8 GPa) and compressive yield strengths (19.1-112.7 MPa) were found to coincide with the range for cortical and cancellous bone. These experimental values correlated well with those predicted by the Gibson-Ashby model. The fatigue strengths at 1 million cycles for all structures measured between 15% and 25% of the

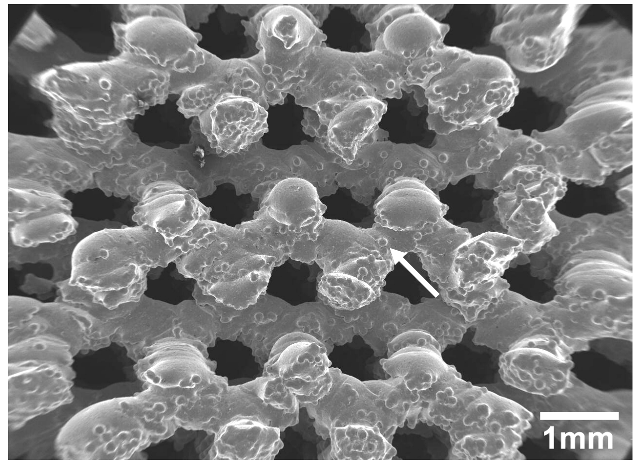

Figure 1. SEM image of 66% porous Ti-6Al-4V structure showing partially sintered titanium particles on a majority of strut surfaces (white arrow).

monotonic yield strength of the structure. These results correlated well with previous fatigue characterizations of fully porous (30% of yield [2]) and porous-coated (20% of yield [3]) titanium structures but were lower than the fatigue strength measured for solid Ti-6Al-4V of the same, acicular microstructure (40% of yield [4]). In-vitro testing is currently being completed, and the results will be presented at the conference.

Conclusions: Porous Ti-6Al-4V structures were fabricated by the EBM technique to have appropriate porosity for bone integration as well as confer sufficient monotonic mechanical properties for implant applications. Because the measured fatigue strengths were close to other, similar porous titanium values, we concluded that these results were not unexpectedly low. However, because the fatigue strengths were lower than those for solid Ti-6Al-4V of the same microstructure, it is concluded that the partially sintered titanium particles observed on the strut surfaces acted to concentrate stress and reduce the fatigue strengths of the porous structures. This work has investigated the fundamental relationship between processing, structure, and properties for these porous titanium structures, which is an important step in demonstrating their potential use in load-bearing bone replacement implants.

References:

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