

Controlling the microstructure and mechanical properties of a metastable β titanium alloy by selective laser melting

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ABSTRACT

Customized titanium alloy devices have become the most attractive orthopaedic implants owing to their effects in mitigating the pain and suffering of patients. This work demonstrates the feasible control of the microstructure, i.e., defects, element diffusion, and phase transformation, and the mechanical properties of a bio-compatible Ti–37Nb–6Sn alloy obtained by selective laser melting (SLM). Defects such as voids and unmelted Nb particles, as well grains with random orientation or columnar grains with {100} fiber texture in the as-fabricated Ti–37Nb–6Sn alloy can be modulated by varying the solidification rate and aging effects during the deposition process. A high energy density input promotes the diffusion of Sn from the grain boundaries to the β -matrix, resulting in an increase in the lattice constants of the β -matrix, with low elastic modulus of the as-fabricated Ti–37Nb–6Sn alloy. However, reheating effects promotes the formation of nanoscale α -phase precipitates both at the grain boundaries and in the matrix. The combined effects of rapid solidification and aging induced by reheating result in a metastable β -type Ti–37Nb–6Sn alloy with a Young's modulus of 66 GPa, ultimate strength of 891 MPa, and elongation of 27.5%. This method can aid the design of customized titanium devices with low elastic modulus for orthopaedic implants applications.

1. Introduction

Titanium alloys are promising biomedical materials owing to their excellent corrosion resistance, mechanical properties, and biocompatibility [1]. According to basic requirements, metallic biomaterials should not contain toxic alloying elements and should exhibit elastic moduli comparable to those of bones. Although Ti–6Al–4V is the most widely used implant material, V and Al can cause allergic reactions, Alzheimer's disease, and neuropathy [2,3]. Moreover, the large Young's modulus mismatch between this alloy and human bones (10–30 GPa) can result in stress shielding [4,5]. Therefore, it is very important to develop toxic element-free titanium alloys exhibiting low modulus, high strength, corrosion resistance, toughness, and plasticity [6–9].

Ti–Nb alloys (containing only non-toxic elements, e.g., Nb, Ti, and Sn) are well suited for biomedical applications because of their low elastic modulus, high strength, superior biocompatibility, and excellent corrosion resistance. These properties can be regulated by modifying the alloy composition and condition-dependent phase transformations, e.g., the addition of β -phase-stabilizing elements such as Nb results in the transformation of the hexagonal close-packed α -phase into the

body-centered cubic β -phase [10]. Moreover, recent experiments have demonstrated that the addition of an insufficient amount of the β -phase-stabilizer to Ti–Nb alloys or their thermomechanical treatment induces the transformation of the disordered β -phase to the metastable orthorhombic α'' -martensite phase, which is primarily accommodated by internal twinning. The transformation of the α -phase to the α'' -martensite phase results in a remarkable decrease in the tensile and yield strengths, with the stabilization of textured α'' -martensite leading to low modulus [11–14]. Therefore, controlling the composition and nanoscale precipitation allows the fabrication of Ti–Nb alloys with high strength (587–779 MPa) and low Young's modulus (57–116 GPa) [15–17].

Selective laser melting (SLM), a process that employs a laser power source to directly and precisely fabricate functional parts based on computer-aided design files, has recently emerged as an advanced manufacturing technology. Hence, Ti–Nb alloys with tailored compositions, which are difficult to fabricate by traditional casting, can be directly manufactured by SLM using accurately controlled ratios of the alloying powders, because they can be melted and solidified in a few seconds under the action of a focused laser beam. Owing to the rapid

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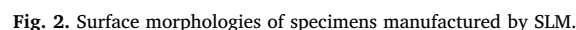
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Sample	h (mm)	P (W)	v (mm/s)	t (mm)	E (J/mm ³)
A1	0.12	225	1200	0.03	52.08
A2	0.12	275	1200	0.03	63.66
A3	0.12	225	800	0.03	78.13
B1	0.05	225	1200	0.03	125.00
B2	0.05	225	800	0.03	187.50
B2	0.05	350	800	0.03	291.67

Therefore, it is imperative to investigate the direct fabrication of customized devices with high strength and low elastic modulus for orthopaedic implants. In this work, biocompatible Ti-37Nb-6Sn alloys were fabricated by SLM. The effect of the scanning process on the tensile properties and microstructure of the Ti-37Nb-6Sn alloy was experimentally investigated. In detail, studies on the modulation of grain size, grain orientation, defects, and phase of the as-fabricated Ti-37Nb-6Sn alloy and the corresponding tensile properties were conducted. Elemental distribution and phase transformations during the SLM process were also characterized.

Pure Ti and Sn powders produced by gas-phase atomization comprised spherical particles with average sizes of 21.7 and 8 μm , respectively. Pure Nb powder prepared by mechanical crushing contained irregularly shaped particles 30.5 μm in size. These three powders were



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