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Heat treatment enhancing the compressive fatigue properties of open-cellular Ti-6Al-4V alloy prototypes fabricated by electron beam melting

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ABSTRACT

In this work, we report the effect of annealing in α+β phase field on the fatigue properties of Ti-6Al-4V alloy meshes fabricated by electron beam melting. The results show that annealing at high temperature near the phase boundary enhances the ductility of the brittle mesh struts due to the formation of coarse α lamellas with a large thickness/length ratio. Accordingly, the fatigue endurance ratio of the studied meshes increases to up to ~0.6, which is much superior to that of the as-fabricated counterparts and comparable to those of dense materials.

1. Introduction

Titanium and titanium alloys based open cellular structures possess low Young's modulus matching to that of the human bone and have the capability of providing space for bone tissue in-growth therefore a better fixation, which renders them being considered as a good option for replacing dense implants [1,2]. Recently, additive manufacturing (AM), as an emerging technology, is capable to realize complex porous patient-specific structures from medical grade metallic powder materials [3–5]. The majority of studies on AM-produced porous titanium alloys have been focusing on the processing and the resultant mechanical properties of (α+β)-type Ti-6Al-4V. It has been reported that the AM-produced Ti-6Al-4V porous structures usually exhibit high strength, lightweight, excellent corrosion resistance, low Young's modulus and good biocompatibility [6–12].

To ensure safety and long term application in human body, the metallic cellular structures should possess superior fatigue properties. A few studies on compression-compression fatigue behavior for Ti-6Al-4V cellular structures fabricated by AM technique indicate that, due to the rough strut surface and brittle deformation behavior, their normalized fatigue strengths are in the range of 0.10–0.25, which are much lower than that for solid Ti-6Al-4V counterparts (about 0.6) [13–16]. Such a significant reduction in normalized fatigue strength is quite different from the scenario for aluminum and its alloys foams, which have a comparable fatigue endurance [17]. As such, two methods have been reported with aim to enhance the fatigue properties of Ti-6Al-4V cellular structures. One is cell shape design. By optimizing the buckling and bending deformation on the struts through cell shape design, the compressive fatigue strength of AM-produced cellular structures can be significantly improved [18,19]. The other is surface smoothening treatment. Chemical etching can significantly smoothen struts surface thereby reducing the stress concentration near the nodes of unit cells. As such the fatigue crack initiation through the struts can be significantly alleviated [20].

From the viewpoint of the microstructure of the struts, the much lower fatigue resistance of the AM-produced Ti-6Al-4V meshes is mainly attributed to the hard and brittle α' martensite usually formed in Ti-6Al-4V porous components, which is detrimental to their ductility and cyclic plastic accumulation during fatigue [13,18]. Thus, in order to improve the fatigue strength of the AM-

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produced porous components, one possible way is to adopt post heat treatment to manipulate the morphology and phase composition contained in the cellular structures. However, few studies have been reported to elucidate the underlying mechanism [20]. In this work, the reticulated Ti-6Al-4V meshes with porosity of 72% were fabricated by electron beam melting (EBM) and the effect of the heat treatment on the morphology and phase composition of the mesh struts and resultant fatigue properties were investigated. The results indicated that by proper annealing treatment, the fatigue endurance ratio of the studied meshes is significantly enhanced up to ~0.5, which is comparable to those of dense materials.

2. Experimental

The reticulated mesh structures of Ti-6Al-4V alloy were fabricated by an EBM system manufactured by Arcam, Sweden (Arcam A1). These monolithic structures were built layer-by-layer using the medical-grade Ti-6Al-4V (ELI) powder precursor with an average diameter of ~50 μm. Each powder layer was created by raking powder gravity fed from two cassettes, heated to ~730 °C by multiple pre-heating scans and then melted the selected layer areas driven by a three-dimensional CAD program created by Materialise/Magics software. The reticulated mesh structure in this study was an ideal mesh structure based on a build lattice unit cell with a cubic shape. Some thin rods with 1 mm in diameter and 60 mm long were fabricated and polished to evaluate the mechanical properties of the mesh struts. Some plates with dimension of 1 mm × 10 mm × 10 mm were fabricated for X-ray diffraction (XRD) tests. The thickness of these plates is similar to that of mesh strut. Some as-fabricated Ti-6Al-4 V meshes, thin rods and plates were heat treated at temperatures between 750 °C and 950 °C for 1.5 h and furnace cooled to room temperature in vacuum, respectively. Some as-fabricated Ti-6Al-4V meshes and thin rods were heat treated at temperatures between 750 °C and 950 °C for 1.5 h and furnace cooled to room temperature in vacuum, respectively. Microstructures of these heat-treated meshes were characterized

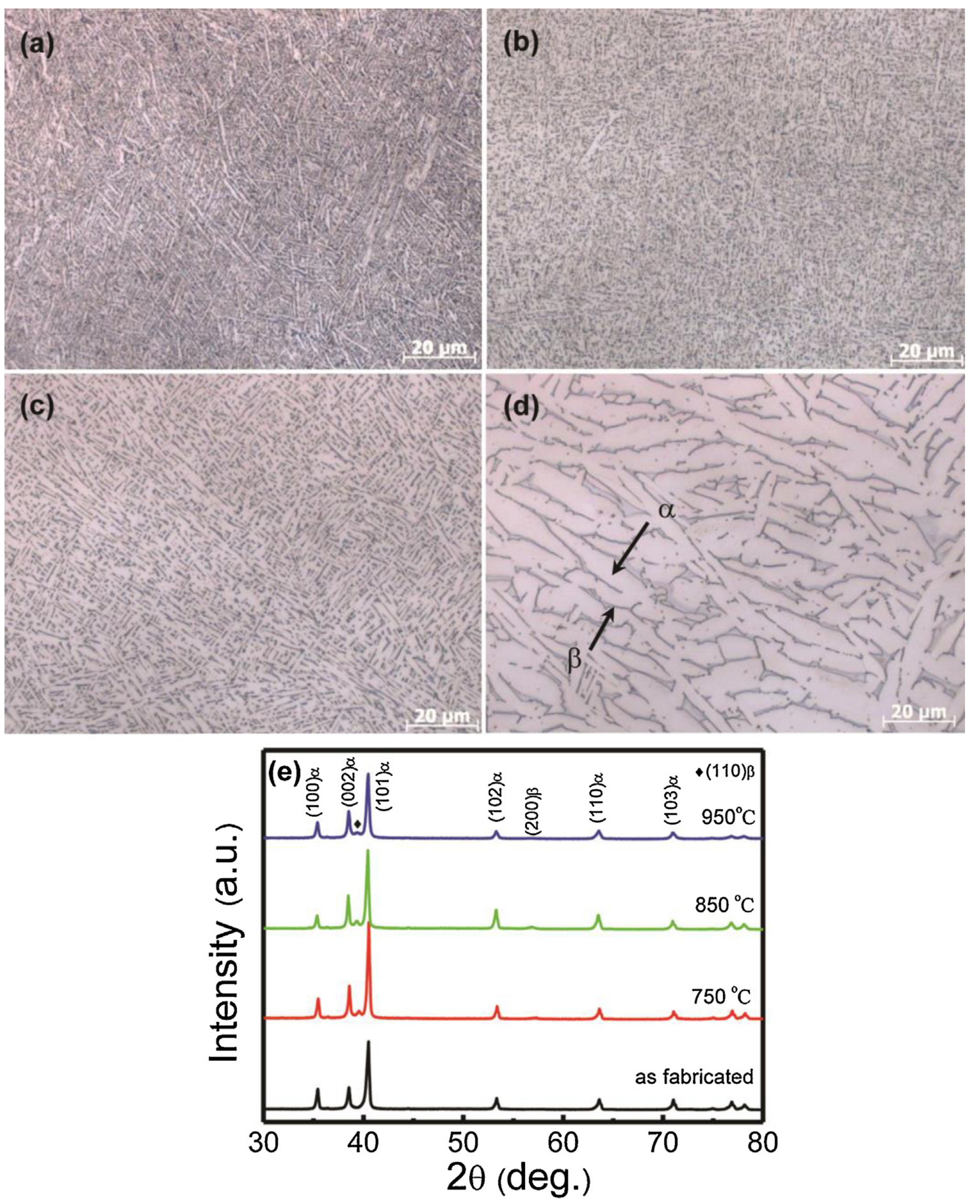

Fig 1. Optical micrographs of Ti-6Al-4V mesh struts manufactured by electron beam melting in different conditions: (a) as-fabricated and annealed at (b) 750 °C, (c) 850 °C and (d) 950 °C for 1 h followed by furnace cooled to room temperature. (e) XRD patterns of the studied samples after different annealing. In (b–d), the α phase is in a bright color and the β phase is in a dark color.

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