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Research paper

Ductility improvement due to martensite α′ decomposition in porous Ti–6Al–4V parts produced by selective laser melting for orthopedic implants

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ABSTRACT

Ti–6Al–4V parts obtained by selective laser melting typically have an acicular α′ martensitic microstructure whose ductility is low. Thus, post-heat treatments are useful for increasing ductility. In this work, the effects of sub-β-*transus* heat treatments on the mechanical properties of Ti–6Al–4V parts with porous structures are correlated with martensite α′ phase decomposition. The precipitation of β phase and the gradual transformation of α′ into α phase by the diffusion of excess vanadium from α′ to β phase are proposed to be the main events of martensite α′ phase decomposition in parts fabricated by selective laser melting. The heat treatment performed at 650 °C for 1 h produced no microstructural changes, but the samples treated for at the same temperature 2 h showed a fine precipitation of β phase along the α′ needle boundaries. The heat treatment performed at 800 °C for 1 or 2 h produced a fine α+β microstructure, in which β phase are present as particles fewer in number and larger in size, when compared with the ones present in the sample heat-treated at 650 °C for 2 h. Heat-treatment of the parts at 800 °C for 2 h proved to be the best condition, which improved the ductility of the samples while only slightly reducing their strength.

1. Introduction

The fabrication of titanium and titanium alloy parts with porous structures offers an alternative to decrease the stiffness of orthopedic implants and overcome undesirable stress shielding, which is a consequence of the high mismatch between the stiffness of the metallic implant and that of human bone. Furthermore, porous structures have additional advantages over full-density material: they are lighter and the architecture of interconnected pores enables new tissue to grow through them, improving implant fixation (Warnke et al., 2009).

Additive manufacturing technologies such as selective laser melting (SLM) and electron beam melting (EBM) allow one to produce parts with controlled internal pore structures or fully densified parts of complex geometries. SLM is a technique

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whereby parts are produced from metal powder, using the energy of a laser beam to selectively promote fusion according to a previously defined CAD model. The process occurs inside a thermally controlled chamber with inert gas (Yang et al., 2002; Vandenbroucke and Kruth, 2007).

Ti–6Al–4V alloy, which was initially developed for aerospace applications, is widely used today in orthopedic implants owing to features such as high strength-to-weight ratio, low Young's modulus, high corrosion resistance and good biocompatibility in the physiological environment (Liu et al., 2004; Geetha et al., 2009). This alloy is also the titanium alloy most widely used in additive manufacturing. Ti–6Al–4V parts produced by SLM present high residual stress in the as-processed state and possess a typically acicular α′ martensitic microstructure. Hence, their ductility is low, but post-heat treatments can be applied to overcome this disadvantage.

There are numerous studies about the effects of heat treatments on the mechanical properties of Ti–6Al–4V alloy obtained by more conventional processes (Ahmed and Rack, 1998; Venkatesh et al., 2009; Dong et al., 2013), and several points regarding this subject are well established. Annealing temperatures lower than 550 °C should be avoided due to very fine Ti_3Al precipitation, which promotes age hardening and embrittlement (Lütjering, 1998). Annealing temperatures above the β-*transus*(super-β-*transus* treatments) should also be avoided, due to excessive grain growth of the β phase in this range of temperatures. Annealing temperatures in the two-phase field (sub-β-*transus* treatments) can improve the mechanical strength and do not significantly reduce ductility (Fan et al., 2011).

More recently, the effects of heat treatments on the mechanical properties of Ti–6Al–4V parts obtained by SLM were reported by Vrancken et al. (2012). These authors showed that the response of SLM material to heat treatment differs considerably from that of conventionally processed Ti–6Al–4V alloy. One of the main causes for the differences is the condition of the starting material. The alloy produced by more conventional processes is in the annealed or heavily deformed condition, while, as stated earlier, SLM parts characteristically have a martensitic α′ microstructure. Therefore, the effect of heating on the martensitic α′ phase must be understood in order to design heat treatments at sub-β-*transus* temperature, aimed at increasing the material's ductility. In an earlier study, we examined the effect of pore size and volume fraction of porosity on the mechanical properties of Ti–6Al–4V porous parts obtained by SLM (Sallica-Leva et al., 2013). The effect of the cooling rate in super-β-*transus* treatments was also analyzed. In this work, we studied the effects of sub-β-*transus* heat treatments on the mechanical properties of Ti–6Al–4V porous structures, emphasizing the role of martensite α′ phase decomposition.

2. Experimental details

The porous part was first designed by CAD, using the cubic body with 15 mm edge created by Parthasarathy et al. (2010), which was reproduced and characterized in a previous study (Sallica-Leva et al., 2013). We used the model with 68% of porosity, a pore size of 1570 μm and strut size of 800 μm. The porous parts were then produced by SLM, using a Ti–6Al–4V pre-alloyed powder as raw material. The following process parameters were selected: 170 W laser power, 1250 mm/s scan speed, 100 μm distance between laser scan lines, and 30 μm layer thickness. Fig. 1 depicts the CAD model and a sample fabricated by SLM technique. The non-heat-treated samples that will be used for purposes of comparison are hereinafter referred to as as-processed samples.

The martensitic α′ microstructure revealed by Kroll's reagent was observed in as-processed samples, as shown in Fig. 2. This structure resulted from the high cooling rate imposed by the SLM process (Elmer et al., 2004; Murr et al., 2009; Facchini et al., 2010). The nitrogen–oxygen level, which was determined by the inert gas fusion method using a LECO TC400 nitrogen–oxygen analyzer, was found to be 0.021±0.003% and 0.170±0.004%, respectively, in the as-processed samples. The as-processed samples exhibited an effective elastic modulus (E_{ff}) of 7.72±0.04 GPa, yield strength (YS) of 129±4 MPa, ultimate compressive strength (UCS) of 163±2 MPa, hardness of 277±9 HV and fracture strain of 8.23±0.40%. Further details about porous parts fabrication and characterization can be found in an earlier paper (Sallica-Leva et al., 2013).

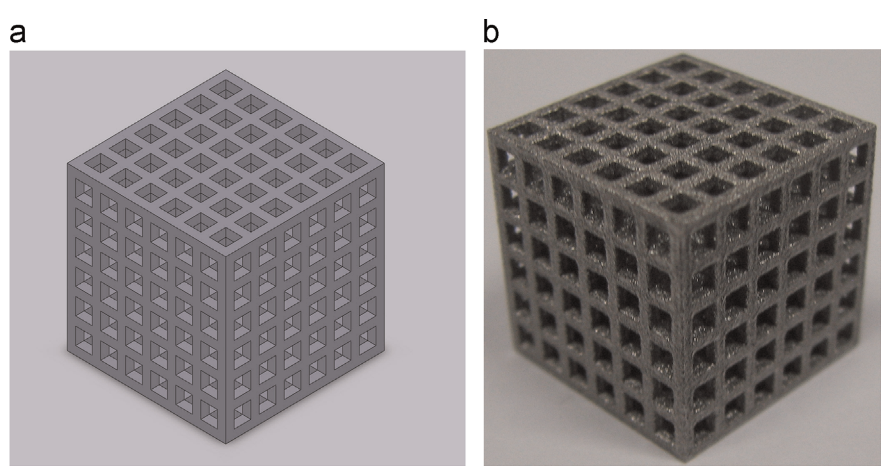

Fig. 1 – (a) CAD model, (b) sample obtained by SLM.