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Selective laser melting of weak-textured commercially pure titanium with high strength and ductility: A study from laser power perspective

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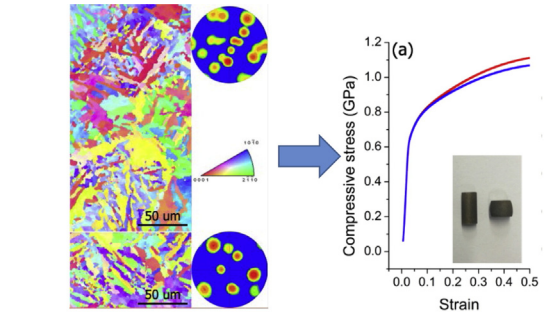
HIGHLIGHTS

- Different laser powers led to different phase formation, microstructure, texture and mechanical properties of SLMed CP Ti.
- A weak-textured CP Ti with isotropic mechanical properties was achieved using high laser power
- A strong-textured CP Ti with anisotropic mechanical properties was obtained using low laser power
- The mechanism was attributed to the formation of α′ phase as a result of the higher cooling rates at high laser power.
- The weak-texture CP Ti showed high ultimate compressive strength ~1.1 GPa with a compressive strain ≥ 50%

GRAPHICAL ABSTRACT



Weak-textured CP Ti fabricated by SLM

Isotropic mechanical properties

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ABSTRACT

In this study, fully dense commercially pure titanium (CP Ti) parts were successfully fabricated by selective laser melting (SLM) using the same optimal laser energy density $\overline{E_p}$ but with two different laser powers: high laser power E_H ~250 W and low laser power E_L ~50 W. It was found that at the same $\overline{E_p}$ different laser powers led to different phase formation, microstructure, texture and mechanical properties of the selective laser melting fabricated (SLMed) CP Ti. A weak-textured CP Ti with isotropic mechanical properties was achieved using E_H while a strong-textured CP Ti with anisotropic mechanical properties was obtained using E_L. The underlying mechanism was attributed to the formation of α' phase in the CP Ti as a result of the higher cooling rates at E_H. The formation of α' phase also contributed to the observed high ultimate compressive strength ~1.1 GPa and high compressive strain ≥50% in the SLMed weak-textured CP Ti at E_H. This study provides important insights into the role of laser energy in the SLM fabrication of CP Ti with tailorable crystallographic texture and thus mechanical properties.

1. Introduction

Commercially pure titanium (CP Ti), as an attractive engineering material, has applications in a wide spectrum of industries including power generation, chemical, petrochemical, heat management, spacecraft and biomedical devices due to its excellent corrosion resistance, good weldability and fabricability as well as excellent biocompatibility [1]. However, its relatively low strength as compared to other high strength Ti alloys impedes its further applications where mechanical properties are also important. Unfortunately, due to the sluggish response of CP Ti to heat treatment, the options for strengthening CP Ti

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are relatively few and limited, mainly solid solution strengthening by oxygen in particular [1]. However, oxygen is detriment to its corrosion resistance and biocompatibility [1]. To address this problem, fabrication of ultrafine grain CP Ti as an alternative is being sought recently to improve its mechanical properties strength while retaining its excellent corrosion resistance and biocompatibility [2].

Recently, selective laser melting (SLM), as a powder based metal additive manufacturing (AM), has enjoyed a rapid development [3]. When compared to traditional fabrication processes, the unique layer-wise fabrication process of SLM renders SLM many advantages e.g. high freedom of customization, high materials usage efficiency and fabrication of complex geometry parts and so on. Importantly, the high heating and cooling rates during SLM enable the fabrication of metal parts with very fine and tailorable microstructure, e.g. Al-Si and Ti alloys, metal matrix composites as well as bulk metallic glasses [4–11]. Similarly, fine microstructures including lath α, acicular α' and refined zig-zag α' can also be manipulated in SLM fabricated CP Ti parts through controlling the process parameters [12,13]. As a result, the SLMed CP Ti shows a high hardness ~3.89 GPa and compressive strength ~1136 MPa [13]. Also important is that no addition of other alloying element is needed and hence no corrosion resistance or biocompatibility sacrifice. This suggests that SLM is a promising alternative to fabrication of CP Ti with fine structure and hence enhanced mechanical properties. It is known that a strong-textured microstructure tends to develop in the SLMed metal parts, e.g. Ta and high-silicon steel due to the existence of directional heat flux and large thermal gradient during SLM [14,15]. This strong textured microstructure will result in anisotropy in mechanical properties of the fabricated metal parts, which is not desirable in many cases. When this comes to CP Ti, this problem becomes severer due to the intrinsic anisotropy of its hexagonal close packed (*hcp*) crystal structure. Previous studies have shown that CP Ti can suffer from cleavage fracture at low temperature and high strain rates when the local normal stress across the cleavage plane exceeds a critical value [1]. Based on this, the crystallographic texture in CP Ti directly affects the propensity for cleavage since the relative orientations of the basal plane and the loading axis affect the normal stress component across the cleavage plane. In addition, the crystallographic texture in CP Ti also plays an important role in determining its biomedical properties [16,17]. This is due to the formation of different oxide layer structures on different crystallographic textures. For example, the surface consisting of more densely packed basal planes promote the formation of Ti-OH which can in turn enhance the cell-substrate interactions [17]. Therefore, understanding the formation of crystallographic texture in SLMed CP Ti and manipulation of the texture is very important and necessary. However, to the knowledge of the authors, no work has been reported on the influence of laser energy on the texture formation in SLMed CP Ti.

In this work, fully dense (relative density ≥ 99%) and crack-free CP Ti (Grade 1) parts were fabricated by SLM using the same optimal laser energy density $\overline{E_p}$ but with two different laser powers: high laser power E_H ~250 W and low laser power E_L ~50 W. The influence of laser power on the phase formation, microstructure evolution, texture and mechanical properties was investigated. A relation between laser power, microstructure and mechanical properties was established and the underlying mechanism was discussed and provided. The findings of this work provide important insights into the role of laser energy in the SLM fabrication of CP Ti with tailorable crystallographic texture and thus mechanical properties.

2. Experimental procedures

CP Ti powder (Grade 1) from LPW, UK was used in this study. The powder size ranges from 15 to 45 μm, as shown in Fig. 1a. Selective laser melting (SLM) was conducted on an in-house built SLM machine equipped with a fibre laser which has a maximum power of 300 W at the part bed. Two sets of optimal processing parameters were used to fabricate fully dense (relative density ≥ 99%) and crack-free CP Ti cubes with a dimension of 10 × 10 × 10 mm (see Fig. 1b). One was using high laser power E_H ~250 W (the SLMed samples were named S_{HP} in the following text) and the other was using low laser power E_L ~50 W (the SLMed samples were named S_{LP} in the following text). The layer thickness was set at 30 μm and protective high purity argon gas was used for all the builds to minimise oxidation.

The phase formation and microstructure of the CP Ti parts were characterized using X-ray diffraction (XRD, Seifert 3003 T/T, Cu Kα radiation, operated at 40 kV and 40 mA with a step size of 0.02° and scanning speed 2°/min) and light optical microscope (LOM). The crystallographic texture and grain size of the fabricated CP Ti parts were studied using electron backscattered diffraction (EBSD) using a TSL orientation imaging microscope system mounted on a Philips XL30 scanning electron microscopy (SEM) with a tungsten gun. The step size was 0.3 μm for all the EBSD measurements.

Compression tests were carried out on cylindrical samples with a diameter of 5 mm and a height of 10 mm on an Instron 5985 machine at a constant strain rate of 1 mm/min. All the cylindrical samples were prepared from the SLMed CP Ti cubes using electric discharge machining (EDM) either along the building direction (BD) or perpendicular to the building direction which is also the scanning direction (SD), as illustrated in Fig. 1c.

3. Results

3.1. Phase transformation and microstructure

The XRD patterns of the CP Ti raw powder and SLM fabricated CP Ti samples S_{HP} and S_{LP} along two different cross-sections (BD and SD) are shown in Fig. 2. It can be seen that both S_{HP} and S_{LP} exhibited similar XRD patterns as the CP Ti raw powder for both cross-sections (BD and SD), signifying that no formation of new phases was detected after SLM. However, the relative peak intensity of (102) and (110) in S_{LP} along the SD cross-section decreases compared with that in the S_{HP} (along both BD and SD cross-sections) as well as S_{LP} (along the BD cross-section). Given that the same XRD experimental settings were used for all the sample measurements, the relative intensity variation implies that a different crystallographic texture was probably developed in the sample S_{LP} along the SD cross-section.

The microstructure of the SLM fabricated CP Ti samples S_{HP} and S_{LP} is shown in the LOM images in Fig. 3. It can be seen that S_{HP} consisted of a large number of acicular-like grains while a small amount of coarse lath-like grains can also be observed. According to previous studies [12], these acicular-like grains were α' phases which were formed as a result of rapid cooling of β phase from β-transus temperature (T_β ~ 890 °C for CP Ti Grade 1). The coarse lath-like grains were α phases which were formed as a result of slow cooling of β phase from β-transus temperature. In contrast, S_{LP} exhibited a very different microstructure, where only elongated and equiaxed grains can be readily seen. These elongated and equiaxed grains were all α phases. In addition, the grains in S_{HP} also had a relatively smaller size than the grains in S_{LP}. This will be detailed in the following section.

3.2. Crystallographic texture

The microstructure of the SLM fabricated CP Ti samples S_{HP} in both BD and SD cross-sections is shown in the EBSD inverse pole figures (IPF) in Figs. 4a and b, respectively. Elongated and equiaxed grains can be observed throughout the whole samples along both the BD and SD cross-sections (Figs. 4a and b). These grains were randomly oriented which can be confirmed by the random colour in the IPF images. The corresponding pole figures (PF) derived from the IPF in Figs. 4a and b are shown as insets. It is clear that the CP Ti sample S_{HP} showed no specific crystallographic orientation preference along both BD and SD cross-sections. The microstructure of the SLM fabricated CP Ti samples S_{LP}