Scripta Materialia 146 (2018) 187–191

Contents lists available at ScienceDirect

Scripta Materialia

journal homepage: www.elsevier.com/locate/scriptamat

Regular article

Achieving superior ductility for laser solid formed extra low interstitial Ti-6Al-4V titanium alloy through equiaxial alpha microstructure

Zhuang Zhao, Jing Chen *, Hua Tan, Guohao Zhang, Xin Lin, Weidong Huang

State Key Laboratory of Solidification Processing, Northwestern Polytechnical University, Youyi Western Road, Xi'an, Shaan Xi 710072, People's Republic of China
Key Laboratory of Metal High Performance Additive Manufacturing and Innovative Design, MIIT China, Northwestern Polytechnical University, Youyi Western Road, Xi'an, Shaan Xi 710072, People's Republic of China

ARTICLE INFO

Article history:
Received 16 August 2017
Received in revised form 12 November 2017
Accepted 14 November 2017
Available online xxxx

Keywords:
Laser solid forming
Titanium alloy
Superior ductility
Equiaxial alpha
Triple heat treatment

ABSTRACT

The limited ductility of laser solid formed (LSFed) titanium alloy is a critical issue, which hinders their potential engineering applications. Here, we reported a largely improved ductility (25.1% total elongation) of LSFed extra low interstitial Ti-6Al-4V titanium alloy with a comparable tensile strength (>860 MPa, international standards) using triple heat treatment. Superior ductility was mainly attributed to the gradual globularization of the α laths during subcritical annealing. The secondary α lamellar obtained by the solution treatment and aging was responsible for the tensile strength. The present findings provide significant guidance for fabricating LSFed titanium alloy having high ductility and good strength.

Laser solid forming (LSF) is one kind of additive manufacturing (AM) technology used to directly fabricate three-dimensional metallic components with complex structures [1–2]. Recently, LSF has been recognized as an attractive technique for fabricating expensive aerospace parts rapidly and cost-effectively. Titanium alloys, especially Ti-6Al-4V/Ti-6Al-4V-ELI (extra low interstitial Ti-6Al-4V) are widely used in the advanced aeronautic and astronautic industries, due to the excellent comprehensive mechanical properties [3–4]. Therefore, much research has been conducted on LSF with this alloy over the last decades. Typical microstructure features of the LSFed Ti-6Al-4V titanium alloy are usually comprised of columnar prior-β grains and complex intracrystalline sub-microstructure (i.e. α phase), such as basket-weave structure, lamellar structure and needle structure containing martensitic α′ [5–7]. This results in the LSFed Ti-6Al-4V titanium alloy being stronger (in terms of strength) than its wrought components. But for industrial applications its tensile ductility and low cycle fatigue property (directly related to the plasticity) need to be substantially improved [8].

Recently, post-LSF heat treatments turned out to be the most promising way to increase ductility. Vrancken et al. [9] annealed the LSFed Ti-6Al-4V titanium alloy at 850 °C/2 h followed by furnace cooling (FC), obtaining a unique coarse α phase and largely improving the elongation from 7.36% to 12.84%. Ren et al. [8] demonstrated that when LSFed Ti-6Al-4V titanium alloy was solutioned at 920 °C for 2 h and aged at 550 °C for 4 h, the elongation would be 18%, which was significantly higher than that of the as-built samples. Liu et al. [10] found that a special bimodal microstructure consisting of crab-like primary α and transformed β was formed by sub-critical annealing in the LSFed near β titanium alloy, which largely increased the tensile ductility (16.5%). However, the improved ductility through annealing or solution treatment and aging (STA) always came at the sacrifice of strength, which usually degraded to a substantially low level. Additionally, another drawback of the LSFed titanium alloy was that the improved ductility was also insufficient (typically the elongation <20%), which still limited their potential use in the advanced aeronautic and astronautic industries.

Generally speaking, an equiaxed-α microstructure is required to obtain superior ductility. This type of microstructure is usually produced by a series of thermomechanical processing (TMP) as a result of deformation and globularization of initially α lamellar [11–13]. However, the microstructure of the LSFed titanium alloy is quite different from that of the TMPed parts, since the rapid cooling promotes the formation of lamellar or acicular α phase, which is inherently less ductile than the equiaxed-α microstructure. Therefore, the objective of this study is to demonstrate an implementable, optimized LSF processing + innovative heat treatment approach that can lead to full globularization of the lamellar α microstructure with superior ductility levels. Additionally, to achieve a good balance of strength and ductility, this approach is also designed to produce a percentage of transformed β microstructure which consists of fine secondary α lamellar (α_s) and retained β phase. This triple microstructure leads to a large increase in ductility without sacrificing strength too much, which still conforms to the ASTM

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* Corresponding author.
E-mail address: phd2003cjj@nwpu.edu.cn (J. Chen).

https://doi.org/10.1016/j.scriptamat.2017.11.021

specification. The globularization mechanism, tensile mechanical properties, and resulting deformation behavior are successively highlighted in the frame of this paper.

In the present study, the Ti-6Al-4V-ELI titanium alloy samples with dimensions of $60 \times 20 \times 80$ mm were fabricated by a LSF system, which consisted of a 6 kW diode laser, a coaxial powder feeder nozzle, a five-axis numerical control working table and an argon purged processing chamber with oxygen content below 50 ppm. The processing parameters were as follows: laser beam power 2100 W, scanning speed 900 mm/min, beam diameter 5 mm, powder delivery rate 12–15 g/min, and overlap ratio 50%. The scanning path was cross-directional mode, meaning that the scanning directions of adjacent layers were perpendicular. Using these parameters, the LSF process exhibited good formability, and the samples were fully dense with lack of pores or fusion defects [14]. The Ti-6Al-4V powders with extra low interstitial (wt%, 0.12Fe-0.08O-0.01C-0.015N-0.009H) prepared by a plasma rotating electrode with a diameter of about 80–120 μm were employed as the cladding materials. Before the LSF experiment, the powders were dried in a vacuum oven for 2 h at 120 ± 5 °C. The forged Ti-6Al-4V plates with the dimension of $150 \times 50 \times 10$ mm were used as substrates for the LSF process. The substrate surface was sanded with SiC paper and cleaned with acetone.

In the following discussion, the triple heat treatment was designed to conduct on the LSFed samples. Fig. 1(a) shows the heat treatment process. Firstly, the sample was sub-critical annealed at 980 °C for 1 h followed by FC with a cooling rate of 10 °C/min. It is well-known that residual stresses, caused by the localization of the thermal input in the LSF process, are almost unavoidable [15]. It may lead to distortion of the samples, as well as to the formation of a dislocation structure in the LSFed pieces. Therefore, at such high temperature, the dislocation can be fully activated with slipping or climbing. Compared to the traditional stress relief annealing, isothermally holding at 980 °C, some of dislocations may be polygonized and form a number of subgrains. It will provide a prerequisite for globularization of the LSFed lamellar microstructure. Additionally, below the β-transus temperature (T_β, 990 °C), some of primary α will be preserved (as shown in Fig. 1b) and form intragranular α nuclei (α_I). These α_I will further promote the growth of the equiaxial α during the following continuous cooling process. Subsequently, to obtain a number of α_s, a STA heat treatment (920 °C/1 h/AC + 600 °C/4 h/AC) was applied following the subcritical annealing, as shown in Fig. 1(a). This heat treatment process was typically applied in our previous studies for LSFed titanium alloy [16]. Moreover, the 980 °C/1 h/WC (water cooling), 980 °C/1 h/FC, and 980 °C/1 h/FC + 920 °C/1 h/AC (air cooling) were also selected to research the microstructure evolution in this process.

Microstructural characterization was carried out by optical microscopy (Keyence VH-Z50L) and scanning electron microscopy (Tescan VEGAIILMH). A commercial image analysis software (Image-Pro-Plus 6.0) was employed for quantitative measurement of the microstructure parameters (volume fraction, width and aspect ratio). A mixture of 1 ml HF + 3 ml HNO_3 + 50 ml H_2O was used as the etching agent. Room temperature tensile tests were performed at a constant crosshead

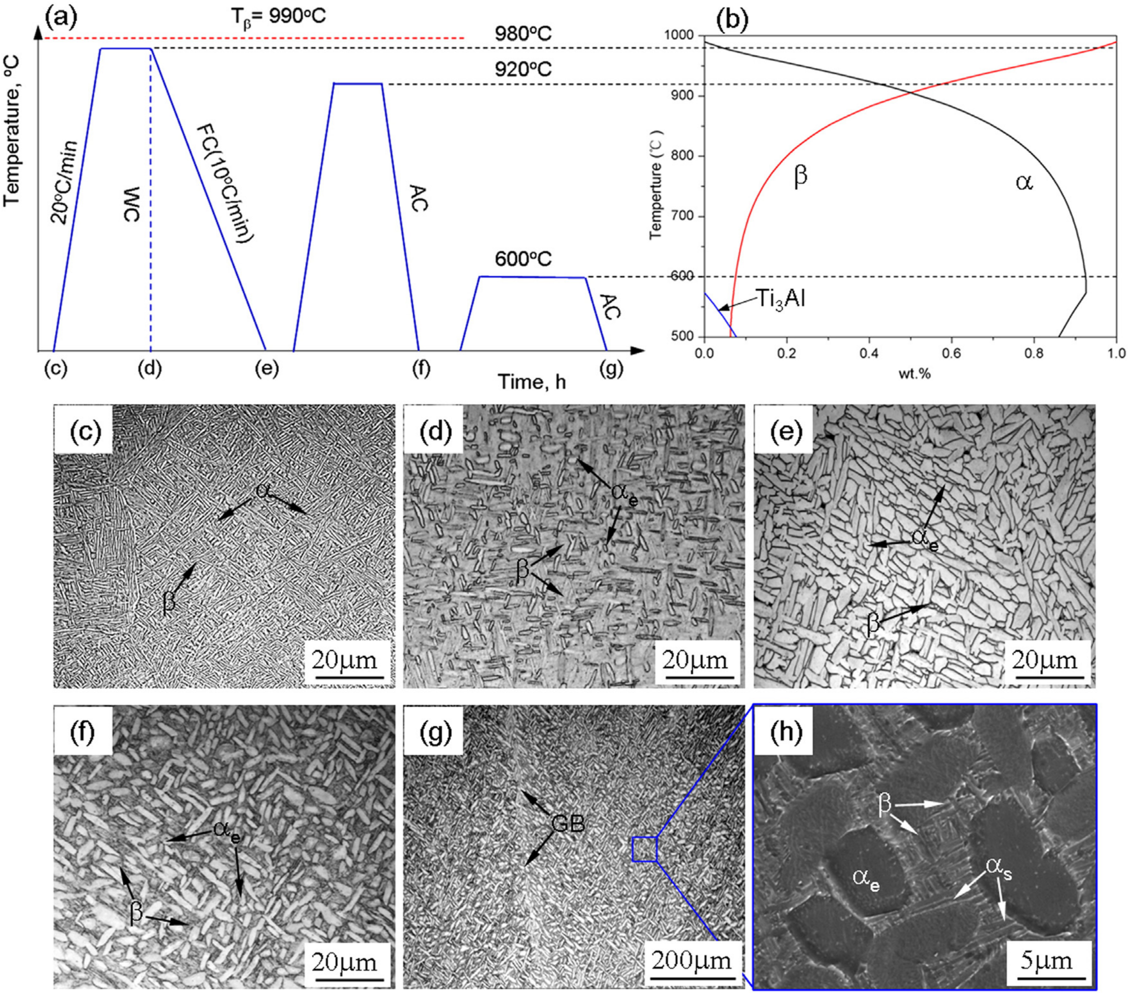

Fig. 1. (a) Schematic illustration of the triple heat treatment; (b) calculated Ti-6Al-4V-ELI phase diagrams by Thermo-Calc software; (c–h) microstructure evolution in the heat treatment process. (c) As-built; (d) 980 °C/1 h/WC; (e) 980 °C/1 h/FC; (f) 980 °C/1 h/FC + 920 °C/1 h/AC; (g) 980 °C/1 h/FC + 920 °C/1 h/AC + 600 °C/4 h/AC; (h) the enlarged microstructure morphology in (g).