Materials Letters 216 (2018) 50–53

Contents lists available at ScienceDirect

Materials Letters

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

The β phase evolution in Ti-6Al-4V additively manufactured by laser metal deposition due to cyclic phase transformations

H.Z. Zhong [a,b], M. Qian [b], W. Hou [a], X.Y. Zhang [c], J.F. Gu [a,c,*]

[a] Institute of Materials Modification and Modelling, School of Material Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China
[b] Centre for Additive Manufacturing, School of Engineering, RMIT University, Melbourne, VIC 3000, Australia
[c] Shanghai Key Laboratory of Materials Laser Processing and Modification, Shanghai Jiao Tong University, Shanghai 200240, PR China

ARTICLE INFO

Article history:
Received 18 August 2017
Received in revised form 25 December 2017
Accepted 28 December 2017
Available online 29 December 2017

Keywords:
Ti-6Al-4V
Additive manufacturing
Laser metal deposition
Cyclic thermal effect
β phase

ABSTRACT

This paper investigates the evolution of the β phase in laser deposited Ti-6Al-4V via track of the cyclic phase transformation processes by dilatation experiments and characterization of the laser deposited microstructures by transmission electron microscopy (TEM) and an energy dispersive X-ray spectrometer (EDS). The formation temperature of the β phase in as-received mill-annealed Ti-6Al-4V decreased with increasing number of thermal cycles at the heating and cooling rates of 50 °C/s, while the vanadium (V) content in the β phase increased with decreasing β phase formation temperature. The distribution of the V content in the β phase in the laser deposited Ti-6Al-4V showed an increasing gradient from the top layer (i.e., the last deposited) to the fourth layer from the top, which is related to the thermal cycles and the formation temperature of the β phase. The formation mechanism of the β phase was discussed based on the experimental observations.

1. Introduction

Research on additive manufacturing (AM) of Ti-6Al-4V continues to receive significant attention due to the importance of this alloy and the difficulties in manufacturing this alloy by the conventional ingot metallurgy and subtractive manufacturing routes. Previous studies have investigated many aspects of the microstructural evolution issues in additively manufactured Ti-6Al-4V [1,2]. However, the evolution of the β phase has not received sufficient attention to the authors' best knowledge. In particular, all fusion-based AM processes are featured by thermal cycles, which affect the evolution of the β phase. Cyclic phase transformations in steel alloys have been studied by researchers [3,4]. In Ti-6Al-4V, the V content in the β phase is closely related to the formation temperature of the β phase but experimental data on the effect of the thermal cycles on the formation temperature of the β phase remains insufficient. This issue affects the current understanding of the microstructural evolution in additively manufactured Ti-6Al-4V.

This paper investigates the evolution of the β phase in Ti-6Al-4V fabricated by laser metal deposition (LMD). A single-track-deposition wall (see Fig. 1) is designed to investigate the evolution of the β phase caused by thermal cycles. The corresponding microstructure is characterized using transmission electron microscopy (TEM). Dilatation experiments are conducted to simulate the effect of thermal cycles on the formation temperature of the β phase in a LMD process.

2. Material and methods

A fiber laser (IPG) with a 1070 nm wavelength was used as the heat source. The laser metal deposition (LMD) process was protected by an argon shielding gas (purity of 99.99%) fed through a coaxial nozzle with a flow rate of 6 L/min. The processing parameters were selected as follows: laser power at 1000 W, beam diameter at 1 mm, laser scan speed at 3 mm/s. and powder feeding rate at 13 g/min. The last four deposited layers were designated as T1, T2, T3 and T4 (Fig. 1(b)), where the top layer T1 experienced one thermal cycle only while T4 underwent four thermal cycles. JEM 2100 TEM (200 KV) coupled with an Oxford energy dispersive X-ray spectrometer (EDS) detector controlled by Oxford Inca software was used to examine the microstructure and measure the vanadium (V) content. TEM samples were obtained by a standard twin-jet electro-polishing technique with a solution of 60% methyl alcohol, 35% n-butanol and 5% perchloric acid at an applied potential of 30 V and at −35 °C. In order to investigate the kinetics of the formation of the β phase, as-received mill-annealed Ti-6Al-4V sam-

* Corresponding author at: Institute of Materials Modification and Modelling, School of Material Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China.

E-mail address: gujf@sjtu.edu.cn (J.F. Gu).

https://doi.org/10.1016/j.matlet.2017.12.140
0167-577X/

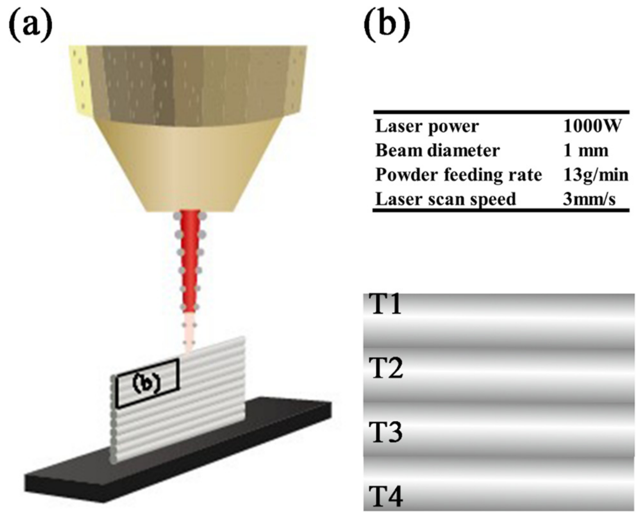

Fig. 1. Illustration of (a) the laser metal deposition (LMD) process used and (b) the last four layers (T1 to T4) in the deposited sample.

ples were machined into Ø4 × 10 mm cylinders for dilatation experiments. The cylindrical samples were subjected to thermal treatments in a DIL805A Quenching Dilatometer (TA; resolution: ±0.05 μm/0.05 °C). As shown in Fig. 2(a), the thermal cycle was repeated four times, where each cycle the sample was heated to 900 °C, the heating and cooling rates were both fixed at 50 °C/s, which was selected to simulation of the high cooling rate in AM.

3. Results and discussion

Fig. 2(b) shows the dilatation curves of as-received ingot Ti-6Al-4V. During heating to the β-transus, the volume fraction of the α phase decreases with increasing temperature by transforming into the β phase until the α phase disappears. The formation temperature of the new β phase as detected by the dilatation experiments decreased when the thermal cycles proceeds from first cycle to fourth cycles (marked by the arrows). The same phenomenon was observed in steel, where the formation temperature of austensite decreased with increasing number of thermal cycles [3]. According to Fig. 2(c), the equilibrium element V content in the β phase (the solid line in Fig. 2c) depends on its formation temperature. A lower formation temperature corresponds to a higher V content. The broken line in Fig. 2c (in blue) refers to the LMD.

Representative α-β microstructure in each layer and the corresponding V content distribution in the β phases are shown in Fig. 3. The β phase showed a similar strip-like shape from layer T1 to layer T4. The V content shown in Fig. 3 was obtained from the analyses of 10 relatively wide β phase strips by TEM-EDS. The distribution of the V content showed a clear gradient and increased progressively from layer T1 to layer T4 or with increasing number of thermal cycles. The trend is consistent with the results shown in Fig. 2, i.e., increasing the number of thermal cycles resulted in a lower formation temperature for the β phase and therefore a higher V content.

The formation mechanism of the β phase in Ti-6Al-4V during heating is not fully understood as yet. Using in-situ EBSD experiments, Humbert and Moustahfid [7] found that the texture of the

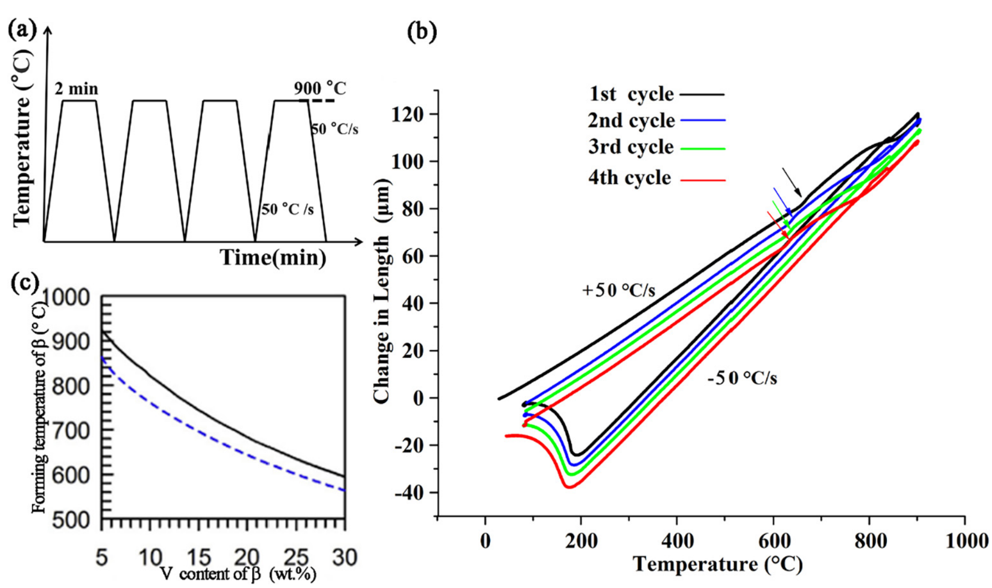

Fig. 2. (a) The four-stage thermal cycles used in the dilatation experiments. The heating rate and cooling rate used in each cycle were fixed at 50 °C/s. (b) Dilatation curves of the mill-annealed Ti-6Al-4V as a function of temperature. (c) Calculated equilibrium V content in the β phase (solid line) as a function of temperature [5,6]. The broken line in blue refers to the case estimated for laser metal deposition (see Fig. 3).