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The spatial distribution of α phase in laser melting deposition additive manufactured Ti-10V-2Fe-3Al alloy

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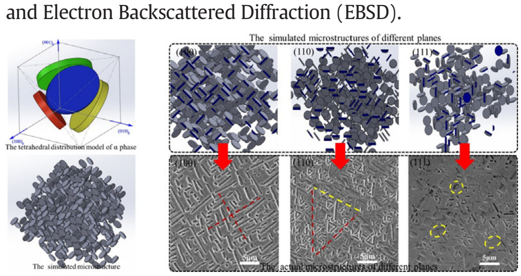
HIGHLIGHTS

- Ti-10V-2Fe-3Al alloy specimen has been fabricated by laser melting deposition additive manufacturing technique.
- A tetrahedral distribution model of α phase and the simulated microstructure have been built.
- The simulated microstructure based on the tetrahedral distribution model has been verified by real microstructure and EBSD.

GRAPHICAL ABSTRACT

In this study, the Ti-10V-2Fe-3Al alloy specimen has been fabricated by laser melting deposition additive manufacturing technique. Three special microstructures are found. A tetrahedral distribution model of α phase and the simulated microstructure have been built to explain the formation of special microstructures. And the simulated microstructure based on the tetrahedral distribution model has been verified by real microstructure and Electron Backscattered Diffraction (EBSD).



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ABSTRACT

Ti-10V-2Fe-3Al alloy specimen has been fabricated by laser melting deposition additive manufacturing technique. Due to the repeated heating and cooling during deposition, complicated and unique phase transformation process take place with forming different microstructures from forging. In this study, a three-dimensional (3D) reconstruction method is used to understand the spatial distribution of α phase in different grains. The results indicated that, in as deposited alloy, α laths has a plate morphology, and they precipitated out from β phase followed a tetrahedral relationship. And the different grain orientation result to the specific different morphology. When the cutting plane parallel to the {100} plane of BCC cell, α laths are perpendicular to each other. If the cutting plane is parallel to the {111} plane, a special morphology with mixture of plate-like and rod-like α phase is founded.

1. Introduction

Ti-10V-2Fe-3Al alloy is a metastable β titanium alloy with high specific strength, fracture toughness, and corrosion resistance [1–5], and it has been used to fabricate the landing gear structure in Boeing 777 and Airbus 350 [6–8]. However, there are some disadvantages of using the traditional manufacturing method to fabricate titanium alloy structural components with complicated shapes, such as the demanding of super large industrial infrastructure and low material utilization rate etc. [9–11]. Moreover, because of a large number of β stabilizing elements added in Ti-10V-2Fe-3Al alloy, β-flecks may form in the melting process or during hot working process, leading to a degradation of performance of the alloy [12,13]. Laser additive manufacturing (LAM) is a potential way to fabricate high density, large and complex Ti-10V-2Fe-3Al aerospace components, due to its many unique merits over conventional manufacturing processes, such as lower cost, shorter cycle times,

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greater flexibility and microstructure stability compared with the traditional manufacturing process, such as casting and forging [9,14].

However, during LAM process, materials suffer very fast cooling with subsequent thermal cycling, resulting a special and complicated microstructures. E.g. the microstructure of Ti-6Al-4V [15–17], Ti–5Al–5Mo–5V–1Cr–1Fe [18,19], Ti-6.5Al-3.5Mo-1.5Zr-0.3Si [20–22] varies with different deposition height along the deposition direction. For example, Zhu [22] revealed some different microstructures with different deposition heights, such as primary superfine basket-weave microstructure, a special bimodal microstructure which is composed of fork-like primary α (α_p) and fine lamellar β transformed matrix, and final basket-weave microstructure. Besides, α laths in grains always distribute followed certain relationship, and the angle between different α laths varies from grains to grains in metallograph. E.g. Zhong et al. [17] reveal that the vertical and the triangular morphologies in laser melting deposited Ti-6Al-4V alloy. The precipitation relationships are also found in forged titanium alloy [23–25]. However, no appropriate space model is proposed to explain the formation relationship between different α laths and why variety relationship are observed.

In order to carefully study the spatial distribution of α phase, three-dimensional reconstruction of α phase in grains is required. There are mainly two reconstruction methods being usually used: the first method is a destructive method based on slicing of samples by either using grinding [26] or focused ion beam (FIB) sectioning [27,28]. The second method is nondestructive method, such as 3D X-ray diffraction (XRD) [29]. By considering of testing costs, the 3D reconstruction method used in this study is the destructive method based on manual grinding sectioning. In this paper, a metastable β titanium alloy Ti-10V-2Fe-3Al was fabricated by laser melting deposition additive manufacturing process. The spatial distribution of α phase in laser melting deposition was investigated by using optical microscope (OM), scanning electron microscope (SEM), transmission electron microscope (TEM) and electron back-scat-tered diffraction (EBSD). The 3D reconstruction method based on manual grinding sectioning is used to investigate the morphology of α lath.

2. Experimental procedure

The laser additive manufactured system consisted of an YSL-10000 fiber laser, a BSF-2 powder feeder together with a coaxial powder delivery nozzle, and a Fagor-8055 computer numerical control (CNC) four-axis working table. This was used to fabricate plate-like specimens. In order to prevent the melt pool from oxidation, the experiments were conducted inside an argon-purged processing chamber with oxygen content <100 ppm. The laser melting deposition additive manufacturing processing parameters were as follows: laser power was 5000 W, beam scale was 6 mm, laser scanning speed was 800–1500 mm/min, and powder feed rate was 15–25 g/min. The dimensions of the plate-like specimen were approximately 300 mm × 300 mm × 35 mm, as shown in Fig. 1.

Metallographic specimens were prepared by conventional mechanical polishing method. A mixture of 1 ml HF, 6 ml HNO3 and 100 ml H2O was used as the etching agent. The microstructures of specimens were characterized by OM and SEM. And OM was carried out using a LECICA-DM 4000 M, SEM was done on a JEOL-6010. Sheet specimens were ion polished and examined using the FEI NANO SEM 430 for EBSD. The scan gap used for as-deposited specimens was 0.1 mm.

The three dimensional (3D) structure of α lath had been investigated as follow: the center of microhardness indentation was used to locate α phase, and the indentation size was used to calculate the polishing depth, as shown in Fig. 2. Then, the work of polishing, locating, taking metallographic photograph was repeated until the tracked α phase being tracked vanish, as shown in Fig. 2(b). Subsequently, the α morphology of each layer was collected and modeled by using 3D modeling software, as shown in Fig. 2(c).

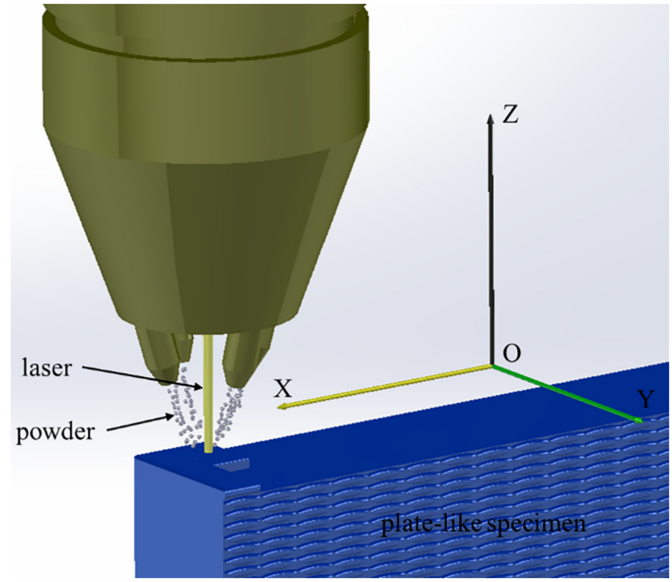

Fig. 1. Sketch map of laser melting deposition showing the three directions: growth direction (OZ), laser scanning direction (OY) and transverse direction (OX).

3. Results and discussion

3.1. Microstructure and 3D structure of α lath

Because of the repeated heating and cooling, the process of phase transformations in as-deposited Ti-10V-2Fe-3Al alloy is very complicated and unique, as shown in Fig. 3. Fig. 3(a) is the macrophotograph of large columnar grain, and shows three different zones with different deposition heights. In the top unstable zone of the large columnar grain, the microstructure is superfine basket-weave microstructure as shown in Fig. 3(b). In the middle transition zone of the large columnar grain, the microstructure changes with deposition height reduction, and as show in Fig. 3(c–f). In the stable zone of the large columnar grain, the microstructure is shown in Fig. 3(g). The microstructure in one large columnar grain varies with different deposition heights along the deposition direction, and this will be discussed in another paper. However, the distribution direction of α phase with different deposition height is similar as red triangle shown in Fig. 3(b–g). That is to say, the distribution direction of α phase in transition zone and stable zone inherit from the super fine basket-weave microstructure.

The low magnification microstructure of stable zone is very fine, as shown in Fig. 4(a). The α phase of as-deposited stable zone presents rod-like shape with 1–5 μm in length, 0.3–0.5 μm in width, and dispersed in β matrix as shown in Fig. 4(b). By observing a large number of grains in stable zone, the α phase is uniformly distributed in each grains because of the thermal cycle, but the morphology vary in different grains as shown in Fig. 4. And the grain boundary α phase is non-uniformly distributed. In some region, the grain boundary α phase is continuous, but in some region, the grain boundary α phase is discontinuous or even invisible as shown in Fig. 4(a). This may cause by the effect of the orientation angle between different grains [30,31].

Through observing a large number of metallographic photos, the vertical and triangular relationship between different α laths are observed. And three kinds of typical microstructure morphologies have been discovered as shown in Fig. 5. The first morphology is that, rod-like α phase distributed similarly along two mutual vertical directions as the dashed line shown in Fig. 5(a), forming the vertical relationship. And no wider α lath is found. The morphology is discovered in most grains in the XOY cross section of sample. The second morphology is the rod-like α phase distributed similarly along three directions as the dotted line shown in Fig. 5(b), forming a triangular relationship. And