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Grain morphology control and texture characterization of laser solid formed Ti6Al2Sn2Zr3Mo1.5Cr2Nb titanium alloy

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ABSTRACT

To better understand β grain morphology control during the laser additive manufacturing of titanium alloys, a damage tolerance α+β titanium alloy, Ti6Al2Sn2Zr3Mo1.5Cr2Nb alloy, was built by laser solid forming (LSF) with different process strategies. The corresponding microstructure and macrotexture were investigated using optical microscopy and X-ray diffraction. Near equiaxed grains, columnar grains (both vertical and inclined) and mixed grain morphology were obtained by suitable control of the processing parameters. The surviving captured powders in the molten pool could act as a substrate core for equiaxed dendritic growth. A lower laser energy density and smaller remelt depth are critical for the formation of equiaxed grains. As expected, near equiaxed grains are more isotropic in crystallographic texture. Both vertical and inclined columnar grains, which exhibit strong but imperfect <100> fiber texture, are easy to obtain using higher laser energy density. The formation of the inclined columnar grains is attributed to the main heat flow direction occurring along the deposition direction and inclining towards the laser scanning direction. The imperfect fiber texture characterization was obtained due to the hereditary crystallographic orientation of the wrought substrate, as certain preferred (100) poles of the substrate present a minimal angle with the temperature gradient at the bottom of the molten pool. Based on the mechanisms of grain morphology formation and the relationship with the processing parameters, the grain morphology and texture in LSFed titanium alloy can be controlled.

1. Introduction

Titanium and its alloys are widely used in the aerospace, biomedical and petrochemical industries due to their high strength-to-weight ratio, good biocompatibility and outstanding corrosion resistance (Banerjee and Williams, 2013). However, end products made of titanium alloys are quite expensive due to the difficulties in the refining, casting, forming and machining processes. Several processes, such as additive manufacture, casting, powder metallurgy and conventional sheet forming, have been examined as possible means of reducing the cost of titanium products (Lutjering and Williams, 2007). Additive manufacturing (AM) is a type of near net shaping technique to produce three-dimensional parts (Huang and Lin, 2014). Laser solid forming is an AM technique for the manufacturing of high-performance complex metallic parts, which has been widely researched in the past decades. In recent years, the LSF process has been considered as an appropriate and cost-effective technology to produce titanium alloy products.

As is well documented, during solidification of the molten pool under laser irradiation, the solid substrate acts as a heat sink, and the as-deposited microstructure mostly presents a directional solidified morphology grown epitaxially from the substrate. Consequently, the typical β grain morphology of LSFed α+β titanium alloys usually consists of coarse columnar grains.

The strongly textured growth of β grains along the build direction generally results in strongly anisotropic mechanical properties in titanium alloys (Carroll et al., 2015). However, in most applications, the desired microstructure is usually represented by fine equiaxed grains, as they exhibit more isotropic and uniform mechanical properties. Among these LSFed titanium alloys, a high-alloy burn-resistant titanium alloy (Ti25V15Cr2Al0.2C) exhibits a very different behavior for the growth of β grains. Wu et al. (2004) studied the influence of the processing parameters on the microstructure of this burn-resistant alloy and suggested that, in contrast to Ti6Al4V, the Ti25V15Cr2Al0.2C alloy prefers to form equiaxed rather than columnar grains for a wide range of processing conditions during LSF process. They reckoned that the formation of equiaxed β grains in the deposited samples was

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attributable to high alloying elements in this alloy and the possible presence of large powder particles. However, as mentioned above, almost no equiaxed β grains could be obtained in the LSFed α+β or near β titanium alloys with less alloying elements. Bontha et al. (2009) calculated the columnar to equiaxed transition (CET) in LSFed Ti6Al4 V alloy and indicated that the CET would occur when the laser power was large enough. Only when the laser power is large enough would the solidification conditions be favorable for the formation of equiaxed dendrites. However, there is a lack of experimental verification for the calculated results. To obtain equiaxed β grains in LSFed α+β titanium alloy, a technology combining additive manufacture with cold rolling was developed. Martina et al. (2015) studied the effects of interpass rolling between the deposited layers by wire + arc additive manufacture technology and found that it can effectively refine the β grains of Ti6Al4V titanium alloy by rolling the deposited layers. Wang et al. (2006) studied the powder and wire feeding additive manufacturing of a compositionally graded titanium alloy by feeding Ti25V15Cr2Al0.2C powders (varying feed rate) and Ti6Al4V wire (fixed feed rate) into the molten pool simultaneously. The result showed that the equiaxed β grains dominate the entire sample when the Ti25V15Cr2Al0.2C powders were added. Clearly, adding an appropriate "grain refiner", such as Ti25V15Cr2Al0.2C powders, is an effective way to obtain equiaxed β grains in the AM process. Considering the LSF process characteristics, the captured powders themselves can act as a 'grain refiner' without introducing any impurities. Gaumann et al. (2001) pointed out that the undissolved powder particles could increase the nucleation density in the molten pool and promote the development of equiaxed dendrites. Liu and Qi (2015a) found that the cold powder particles stuck on the surface of the molten pool could act as a substrate core for equiaxed dendritic growth, but the occasional presented stuck powder affects the final grain morphology less. More recently, it was found that equiaxed β grains could substitute for columnar β grains in response to the increasing powder feed rate in Ti6.5Al3.5Mo1.5Zr0.3Si alloy (Wang et al., 2015) and Ti6Al2Sn2Zr3Mo1.5Cr2Nb alloy (Zhang et al., 2016). A high powder feed rate and a slow scanning velocity were shown to be important for the formation of equiaxed β grains when a single wall structure was fabricated by an LSF process. The partially melted powders were found to provide heterogeneous nucleation for the growth of equiaxed dendrites (Zhang et al., 2016). Without complex extra accessories or introduced impurities, this approach seems to be attractive for the control of the β grain morphology of the LSFed α+β titanium alloys.

Given the deficiency of strongly textured columnar grains and the desire of randomly textured equiaxed grains, a better and deeper understanding of the formation mechanism and texture characteristic of equiaxed grains should be obtained to achieve a more accurate control of the microstructure, especially the β grain morphology, in LSFed α+β titanium alloys. In the present study, the recently developed damage tolerance titanium alloy, Ti6Al2Sn2Zr3Mo1.5Cr2Nb alloy was used as experimental materials and fabricated via the LSF process. This α+β titanium alloy has shown promise for application in the aviation industry due to its high strength (>1100 MPa) and excellent fracture toughness (>90 MPa $m^{1/2}$) (Zhao et al., 2004). The aim of this study is to further understand the formation mechanism of β grain morphology and the effects of processing parameters on grain morphology evolution during the LSF process. The effects of laser energy density E (the energy applied to build per unit weight of a cladding) and cladding layer temperature (controlled by interrupting the deposition process) on grain morphology evolution were investigated. The effect of substrate orientation on the LSFed texture was also investigated.

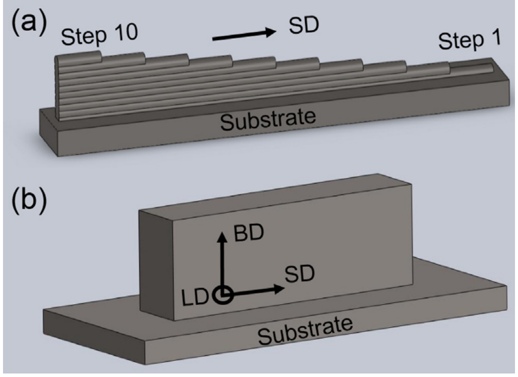

Fig. 1. Schematic illustration of LSFed samples. (a) the stair-like sample, (b) the blocky sample.

2. Experimental procedures

2.1. Production of test specimen by LSF process

The experiment was conducted on LSF equipment consisting of a 4 kW continuous wave CO_2 laser, a 5-axis numerical control working table, a lateral powder feeding nozzle and an argon gas chamber with oxygen content below 50 ppm. Ti6Al2Sn2Zr3Mo1.5Cr2Nb spherical powders produced by the plasma rotating electrode process (PREP) were used as the deposited material. The powder size ranges from 80 μm to 150 μm. The powders were dried in a vacuum oven for 2 h at 120 ± 5 °C to eliminate moisture absorption and ensure the powders have good flow ability. Wrought Ti6Al2Sn2Zr3Mo1.5Cr2Nb plates with dimensions of $104 \times 6 \times 45\ mm^3$ were used as the substrate for the LSF process. The substrate surface was ground with SiC paper and then degreased with acetone and ethanol.

In this study, the unidirectional scanning strategy was adopted to fabricate all of the samples. In unidirectional scanning, the laser always starts from the same side of the deposited sample. The nomenclature and processing parameters used are listed in Table 1. Three different processing strategies were adopted, and listed as follows:

Strategy I: Stair-like sample. A ten-layer one-track stair-like sample was fabricated with a lower laser energy density to investigate the as-deposited microstructure. A schematic of the stair-like sample is shown in Fig. 1a. The stair-like sample has two advantages: i) high-temperature β morphology could be remained due to less thermal input and accumulation, so the original β solidification microstructure could be observed, and ii) the microstructure evolution could be displayed layer by layer.

Strategy II: Continuously deposited samples. Three blocky samples with 5 tracks and 45 layers were deposited continuously with higher energy density. The schematic of the blocky sample is shown in Fig. 1b. Samples CD-2 and CD-3 were fabricated via the same processing parameters to investigate the stability of the LSF process.

Strategy III: Discontinuously deposited samples. During LSF of sample DD-1 with 30 tracks and 45 layers, the deposition process was paused once to allow the already-deposited layers to cool down during the LSF process. Sample DD-2, with 5 tracks and 45 layers, was fabricated as a function of the nominal Z increment (which was increased from 0.5 mm to 1.1 mm). The already-deposited layers were air cooled for 1 min every time we changed the nominal Z increment during the LSF process.