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Enhanced compressive strength and tailored microstructure of selective laser melted Ti-46.5Al-2.5Cr-2Nb-0.5Y alloy with different boron addition

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ABSTRACT

The microstructures and compressive properties of Ti-46.5Al-2.5Cr-2Nb-0.5Y alloy with varied boron (B) addition processed by selective laser melting (SLM) had been systematic studied. With increasing the B content from 0 to 2 wt%, the average grain size of SLM-processed Ti-46.5Al-2.5Cr-2Nb-0.5Y/B composites decreased from 16.64 µm to 5.66 µm, meanwhile, the {0001} texture index and high angle grain boundaries (HAGBs) increased from 10.78 and 87.9% to 22.69 and 94.4%. The phase evolution mechanism of Ti-46.5Al-2.5Cr-2Nb-0.5Y/B composites during the SLM process can be summarized as: firstly, β and B phases precipitated out from the liquid phase, then the β phase transformed to α phase and part of the α phase transferred to γ phase, later, some new phases of TiB_2 and AlB_2 emerged by the diffusion mechanism of B, Ti and Al atoms, and then the β and α phases orderly transformed to B_2 and α_2, lastly, the γ, B_2, B, TiB_2, AlB_2 phases in a range of several hundred nanometers were randomly distributed within the α_2 matrix. Due to the grain refinement strengthening mechanism, the compressive strength and strain of Ti-46.5Al-2.5Cr-2Nb-0.5Y/B parts increased to the maximum of 1610.53 MPa and 5.17%.

1. Introduction

TiAl alloys are highly promising for high temperature applications in aerospace and automotive fields due to their attractive advantages such as low density, excellent high temperature strength and superior oxidation resistance properties [1–4]. However, TiAl components are extremely susceptible to crack due to their relatively low ductility, poor fracture toughness and bad hot workability beyond 800 °C [5,6]. Therefore, the practical application of TiAl alloys have been hindered. In this case, strategies to improve both the room temperature ductility and fracture toughness of TiAl alloys have received a great deal of interest in recent years [7,8].

As is known, the room temperature ductility and fracture toughness of TiAl alloys highly depend on their microstructure features [9]. The TiAl alloys with refined microstructures often provide superior performances including strength, ductility, hardness and so on [10]. Chen et al. [11] demonstrated that both the room temperature tensile strength and ductility of TiAl alloys increased with the decrease of inter-lamellar spacings. Nie et al. [12] pointed out that the relationship between strength, ductility and inter-lamellar spacings obeyed the Hall-Petch law. Recently, alloying is one of the popular and effective methods to control the microstructures and improve the ductility as well as fracture toughness of TiAl alloys [13]. Based on the previous works [13,14], these alloying elements can be classified into three categories: (i) the first group are Y, V, Mn and Cr for increasing the ductility of TiAl alloys; (ii) the second group are Nb, Ta and W for improving the oxidation resistance of TiAl alloys; (iii) the third group are B, C and Si for promoting the microstructure dispersion and grain refinement of TiAl alloys. In most of these alloying elements, B plays an important role in improving the fracture toughness and ductility of TiAl alloys [13]. Currently, some researches have been carried out to study the effect of B on the microstructure evolution and mechanical properties of TiAl alloys. Zhang et al. [15] studied a kind high Nb-TiAl ingots with various B levels using annealing treatment in a single α phase field, the results suggested that the width of coarse grained zone was significantly refined with the increase of B content. Luo et al. [16] investigated the effect of B in refining the lamellar microstructure of TiAl alloys fabricated by spark plasma sintering, the results indicated that B acted as obstacles to the growth of α grains at high temperature, as a result, the B contained TiAl alloys exhibit both an elevated ductility and tensile strength as compared to the B-free counterpart. Hu et al. [17] studied the influence of B addition on tensile ductility of a lamellar TiAl alloy fabricated by cold-hearth plasma arc melting and investment casting, the results suggested that the B was the predominant factor

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influencing the ductility and tensile strength. Although these above mentioned traditional processing methods were capable of fabricating B contained TiAl parts with relatively satisfied properties. However, heterogeneous microstructures were inclined to produce in the B contained TiAl alloys [18]. Therefore, the above mentioned traditional technologies often required series of post heat treatment steps (i.e. ageing and annealing) to improve the microstructure uniformity [18]. Besides, these traditional methods showed little advantages in fabricating B contained TiAl parts with complex structure. Hence, the processing technology of TiAl/B composites should be further development.

In recent years, additive manufacturing (AM), as one of the rapidly developing advanced manufacturing technologies, provides new insight into manufacture complex shaped parts directly from three-dimension (3D) CAD models [19,20]. Nowadays, several studies had successfully applied AM technologies in the fabrication of Ti-base alloys. For instance, Bermingham et al. [21,22] systematic investigated the effect of trace elemental B on the microstructure and tensile strength of Ti-6Al-4V during additive layer manufacturing (ALM), the result suggested that trace B addition (0.13 wt%) to Ti-6Al-4V produced a fine equiaxed α-grains in ALM-processed parts and thus showed up to 40% improvement in ductility with no loss in tensile strength as compared to the unmodified Ti-6Al-4V parts. Mahbooba et al. [23] explored the influence of B addition on the microstructure and bulk mechanical properties of Ti-6Al-4V samples fabricated by electron beam melting (EBM), with the results indicated that the addition of 0.25–1.0 wt% B progressively refined the grain size, and thus improved hardness and elastic modulus.

In most of the AM technologies, selective laser melting (SLM) is capable of fabricating fully dense metal components with complex geometry [24,25]. Therefore, SLM exhibits great potential in fabricating TiAl/B parts. However, to the best of authors' knowledge, no investigations had been conducted to study the TiAl/B composites processed via SLM. Thus, the influence of B content on the grain orientation, phase evolution mechanism and mechanical properties of SLM-processed TiAl alloys were not clarified. In this paper, SLM was applied to fabricate TiAl/B composites. The microstructure, texture evolution, phase transformation with various B content had been systematically investigated. The mechanical properties in terms of compressive strength and strain were also assessed. The ambition of this work was to establish a relationship between B content, microstructure characteristics and compressive properties of TiAl/B composites processed by SLM.

2. Experimental procedures

2.1. Materials

Gas atomized Ti-46.5Al-2.5Cr-2Nb-0.5Y (at%) powder with a neat size distribution of 10–50 μm was supplied by Beijing Institute of Aeronautical Materials (BIAM, Fig. 1(a)), obviously, most of the Ti-46.5Al-2.5Cr-2Nb-0.5Y particles implicated regularly spherical morphology with a smooth surface. Purity B powder with a few traces of other elements (99% B, < 0.03% Ti, < 0.003% Al, < 0.029% Cr, < 0.002% Nb, < 0.006% O, < 0.029% Si) was provided by Aladdin Inc. (Fig. 1(b)), and the B particles implicated an irregular shape with a size distribution of 1–4 μm. Four different TiAl/B composites containing 0, 0.5, 1, and 2 wt% B were prepared by mechanical ball milling with a planetary ball mill machine (QM-3SP4, Nanjing Nan Da Instrument Inc., China). The ball-to-powder weight ratio, main disc rotation speed and milling time were set as 4:1, 250 rpm and 8 h, respectively. In addition, the milling process was carried out under argon atmosphere with a 30-min milling and 10-min pause combination to protect the TiAl/B composites from oxidation. Fig. 1(c) implicated the powder morphology of TiAl/B composite with 2 wt% B content, apparently, the TiAl/B composite also showed a spherical morphology and the B particles were uniformly attached on the surface of TiAl matrix. In order to further verify the B particles, EDS-point was carried out on "P1" and "P2" in Fig. 1(c) with the results were displayed in Fig. 1(d) and (e), respectively. It can be easy found that "P1" was consisted by B element while "P2" was mainly comprised with Ti, Al, Cr, Nb, Y and B elements. Thus, it was accordingly concluded that B particles were uniformly distributed in the Ti-46.5Al-2.5Cr-2Nb-0.5Y matrix. The particle size distribution of TiAl/B composite with 2 wt% B content was shown in Fig. 1(f), obviously, the size distribution was quasi normal distribution with the average particle size was determined to be 22.4 ± 1.5 μm, which was very suitable for SLM process.

2.2. SLM process

A HRPM-II type SLM system (Wuhan Huake 3D Ltd., Wuhan, China), as schematically illustrated in Fig. 2(a), was introduced for TiAl/B samples preparation. The SLM system were consisted of a continuous mode 400 W fiber laser (SP-400C, SPI Lasers, America), a scanning galvanometer system (HURRY SCAN-30, SCANLAB, Germany), an oxygen detector and a computer system for process control. Cubical samples ($10 \times 10 \times 10\ mm^3$) were fabricated on a leveled pure Ti substrates under a high purity argon atmosphere with an overpressure of 10–12 mbar to protect the TiAl/B parts from oxidation. According to a large number of previous SLM experiments, the following optimized SLM parameters were set as follows: laser power (P) = 250 w, laser scanning speed (V) = 600 mm/s, hatching distance (H_s) = 100 μm and layer thickness (D) = 30 μm [26,27]. With respect to the SLM process, the laser scanning diagrammatic and scanning strategy were shown in Fig. 2(b) and (c), respectively. Long bidirectional scanning vectors scanning strategy was used for the cubic sample fabrication. For simplicity, SLM-processed TiAl/B samples with 0, 0.5, 1, and 2 wt% B content were named as S0, S1, S2 and S3. According to the "Archimedes principle", the relative densities of S0, S1, S2 and S3 were determined to be 97.7 ± 1.5%, 96.8 ± 1.3%, 96.1 ± 1.4% and 95.5 ± 1.6%, respectively.

2.3. Microscopic and mechanical property characterization

The particle size distribution of TiAl/B composites were studied by a Mastersizer 3000 type laser diffraction particle size analyzer (Malvern, UK). The phase identification was performed by X-ray diffraction (XRD) using a XRD-7000S (Shimadzu, Japan) type machine with a Cu tube radiation at 40 kV and 30 mA, the diffraction angle of 2θ varied from 20° to 110° with a scan rate of 10°/min and a step size of 0.02°. An Automet300 type automatic polishing machine (Buehler, America) was used to ground and polish the samples of S0, S1, S2 and S3. Then all the samples were electrolytic polished (LectroPol-5, Struers, Denmark) with A3 reagent (vol.90% ethanol + vol.10% perchloric acid) at 25 V and 15 s for electron backscattered diffraction (EBSD) test. The EBSD was performed using an Quanta 650 FEG type scanning electron microscope (FEI, USA) equipped with an EDAX EBSD detector, then the EBSD data was analyzed by a TSL orientation imaging microscopy (OIM) analysis software (EDAX, EDAX Inc., USA). Transmission electron microscope (TEM) and high resolution transmission electron microscope (HRTEM) were performed on a JEOL-2100 type machine (LaB_6 filament, JEOL, Japan). For TEM and HRTEM analysis, thin foils were prepared. Firstly, the foils were mechanically grinded to a thickness of about 50 μm, then punched 3 mm disks from the foils, lastly, the disks were electro polished using a dual jet polishing system at 5 eV. The compressive strength tested under quasi-static uniaxial compression (compressive strain rate of $1 \times 10^{-4}\ s^{-1}$) by a AG-100KN type universal material testing machine (Shimadzu, Japan). The cylindrical compressive specimens with diameter of 3 mm and height of 7.2 mm were cut from the SLM-processed TiAl/B samples. Each samples of S0, S1, S2 and S3 were tested 5 times, then the compressive strength were averaged.