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Microstructure and tensile properties of laser melting deposited Ti–5Al–5Mo–5V–1Cr–1Fe near β titanium alloy

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ABSTRACT

A near β titanium alloy Ti–5Al–5Mo–5V–1Cr–1Fe is fabricated by laser melting deposition (LMD). The evolution of its macrostructure and microstructure during LMD process are systematically studied. Then the relationship between the microstructure and tensile properties is further investigated. The macrostructure exhibits unique bamboo-like β grain morphology, which forms during the solidification and remelt treatment during the LMD process. The microstructures exhibit fine basketweave microstructure and continuous grain boundary α (α_{GB}), whose formation is associated with the complex thermal cycling treatment. Interestingly, an unique fork-like α is observed but gradually disappears during the evolution process of microstructure. The underlying mechanism is proposed. Besides, tensile tests show that the fine microstructure results in high strength, and the continuous α_{GB} causes the low ductility and intergranular fracture. Meanwhile, the cracks are prone to propagate along the interface between the columnar and equiaxed regions.

1. Introduction

Laser melting deposition (LMD) is one of the new additive manufacturing techniques that fabricates full density near-net-shape metal components layer-by-layer using metal powders [1–4]. The LMD is particularly appealing for titanium aerospace components because it can greatly reduce the buy-to-fly ratio and lead time for production. Moreover, LMD can fabricate complex aerospace components which are hardly obtained by conventional manufacturing processes [5–7]. Thus, extensive researches have been carried out to investigate laser melting deposited titanium alloys [8–10]. Till now, most of these related studies are performed on near α and α+β titanium alloys, including Ti–6Al–4V [5,10–15], Ti–6Al–2Zr–1Mo–1V [16] and Ti–4Al–1.5Mn [1]. The investigations of laser melting deposited near β and β titanium alloys are very limited.

Near β and β titanium alloys (VT22, Beta *C*, Ti-15-3 and Ti-10-2-3 etc.) are the most versatile class of titanium alloys [17,18]. They offer the highest strength to weight ratios and very attractive combinations of strength, toughness, and fatigue resistance at large cross sections, thus there is the general tendency that near β and β titanium alloys are increasing in application in the area of aerospace application [6]. Of special interest is whether LMD can fabricate near β and β titanium alloys with good mechanical properties. What is the correlation between LMD processing, microstructure and mechanical properties for near β and β titanium alloys? The main objective of the present work is preliminary addressing these questions.

Here, a typical near β titanium alloy Ti–5Al–5Mo–5V–1Cr–1Fe (VT22) is selected and fabricated by LMD. Then, the macro and microstructures, as well as their evolution during LMD process are investigated. In addition, the tensile tests are performed to address the effect of the macro and microstructures on the tensile properties, and determine whether it can fulfill the mechanical property requirements for aerospace application [19].

2. Experimental procedure

A laser melting deposition system (see Fig. 1) was used to fabricate plate-like sample with dimensions about 200 mm (along laser deposition direction) × 100 mm × 20 mm (along laser scanning direction). The system consisted of an 8 kW continuous wave CO_2 laser, a BSF-2 powder feeder together with a co-axial powder delivery nozzle, and a Fagor-8055 computer numerical control (CNC) four-axis working table. The LMD processing parameters were as follows: laser power was 5000 W, laser beam diameter at melting pool was 5 mm, laser scanning speed was 800–1500 mm/min, powder feed rate was 15–25 g/min, layer thickness was about 2 mm, and hatch distance was 8 mm. To prevent the melt pool

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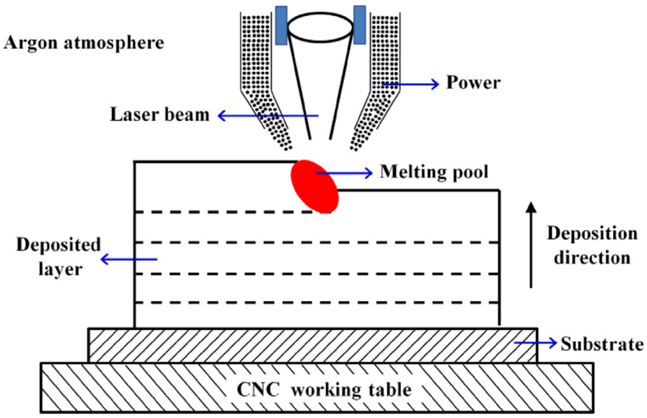

Fig. 1. Schematic illustration of laser melting deposition system.

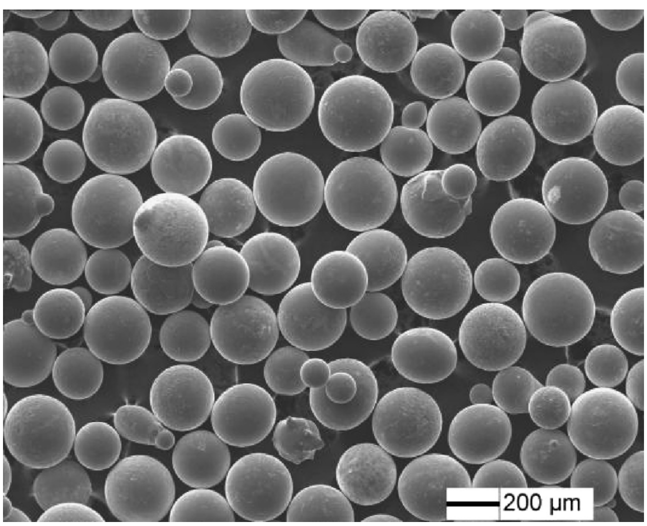

Fig. 2. SEM image showing characteristic morphology of Ti–5Al–5Mo–5V–1Cr–1Fe powders.

from oxidizing, the experiments were conducted inside an argon-purged processing chamber with oxygen content less than 100 ppm. The powder was produced by plasma atomization. It was spherical with diameter mainly from 100 to 300 μm as shown in Fig. 2.

After LMD, cubic specimens ($12 \times 12 \times 12$ mm^3) were cut from the plate-like sample by electric discharge wire. These specimens were used for microstructure observation. Metallographic specimens were prepared by conventional mechanical polishing method. A mixture of 1 ml HF, 6 ml HNO_3 and 100 ml H_2O was used as the etching agent. The microstructures of specimens were characterized by optical microscopy (OM) and scanning electron microscopy (SEM). It should be noted that the as-deposited Ti–5Al–5Mo–5V–1Cr–1Fe alloy hardly exhibited clear β grain morphology by the etching method (see Fig. 6). Thus, a heat treated sample was selected to show the clear vision of β grains at low magnification (see Fig. 3). The heat treatment process was: 860 °C (0.5 h) followed by air cooling, and did not lead to remarkable changes of as-deposited β grain morphology because the heating temperature was below β-transus temperature (880 °C), the α phase in β grain boundary would prevent the β grain growth. The chemical composition (wt%) of the as-deposited specimen was as follows: 5.5% Al, 4.82% Mo, 4.82% V, 1.02% Cr, 1.05% Fe, 0.024% C, 0.021% N, 0.10% O, 0.0028% H and Ti as the remainder. The contents of these elements were in agreement with the standard of Ti–5Al–5Mo–5V–1Cr–1Fe alloy [19,20].

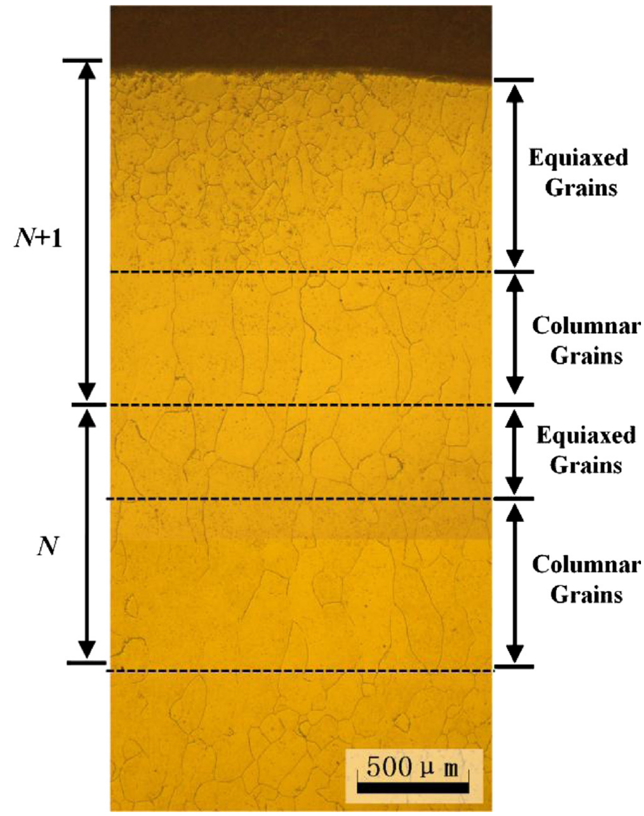

Fig. 3. OM micrograph showing the β grain morphology in the last two layers of laser melting deposited Ti–5Al–5Mo–5V–1Cr–1Fe alloy. The β grains in a single layer exhibit bamboo-like β grain morphology.

The tensile tests were based on the test standard of ISO 6892-1: 2009. Round specimens with 5 mm diameter, 35 mm gauge length and 71 mm total length were prepared for tensile tests at room temperature. Here, the axial direction of tensile specimens was parallel to the deposition direction. The mechanical properties were characterized by averaging the measured values for five tensile specimens. The fracture surfaces and cross sections of the tensile test specimens were examined by SEM and OM, respectively.

3. Results and discussion

This research is aimed at obtaining an insight into the correlations between LMD processing, microstructure, and properties of laser melting deposited Ti–5Al–5Mo–5V–1Cr–1Fe alloy. Then, to investigate the macrostructure (β grains) and microstructure (α phase) evolution during the LMD process, the last several layers will be observed and discussed. Afterward, the tensile property and its relationship with the macro and microstructures are studied.

3.1. Macrostructure evolution

The β grain morphology in the last several layers is observed as shown in Fig. 3. In the last layer ($N+1$), there are columnar grains at the bottom of the layer, while equiaxed grains exist at the top of the layer. The columnar grains are 100–300 μm in width and 0.5–1 mm in height. The equiaxed grains are fine with the diameter about 50–100 μm. In layer N, it exhibits bamboo-like β grain morphology (see Fig. 3), which also consists of columnar grains and equiaxed grains. But the equiaxed grains grow coarse