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Influence of heat treatments on microstructure and mechanical properties of laser additive manufacturing Ti−5Al−2Sn−2Zr−4Mo−4Cr titanium alloy

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Abstract: The effect of heat treatments on laser additive manufacturing (LAM) Ti−5Al−2Sn−2Zr−4Mo−4Cr titanium alloy (TC17) was studied aiming to optimize its microstructure and mechanical properties. The as-deposited sample exhibits features of a mixed prior β grain structure consisting of equiaxed and columnar grains, intragranular ultra-fine α laths and numerous continuous grain boundary α (α_{GB}). After being pre-annealed in $\alpha+\beta$ region (840 °C) and standard solution and aging treated, the continuous α_{GB} becomes coarser and the precipitate free zone (PFZ) nearby the α_{GB} transforms into a zone filled with ultra-fine secondary α (α_S) but no primary α (α_P). When pre-annealed in single β region (910 °C), all α phases transform into β phase and the alloying elements distribute uniformly near the grain boundary. Discontinuous α_{GB} and uniform mixture of α_P and α_S near grain boundary form after subsequent solution and aging treatment. The two heat treatments can improve the tensile mechanical properties of LAM TC17 to satisfy the aviation standard for TC17.

Key words: laser additive manufacturing; TC17 titanium alloy; heat treatment; microstructure; mechanical properties

1 Introduction

Titanium alloys are widely used in aerospace industries due to their high specific strength, good room and high temperature mechanical properties and excellent corrosion resistance [1−3]. Ti−5Al−2Sn−2Zr−4Mo−4Cr (named TC17 in China and Ti-17 in America) is a near β titanium alloy mainly used to fabricate the compressor disk, blade or integrated blisk components of advanced aircraft engines at temperatures up to 450 °C [4,5]. Manufacturing these large and key load-bearing titanium alloy components by traditional wrought-based processes usually results in time-consuming, low materials utilization ratio and high buy-to-fly ratio. These shortcomings could be obviously overcome by the rapidly developing laser additive manufacturing (LAM) technique, a rapid solidification process based on layer-by-layer materials melting and depositing to fabricate fully dense near-net-shape metallic components [6−10].

Due to the near-net shape nature of LAM process, the LAM components cannot be post-deformed and the heat treatment is one of the most important approaches to optimize the microstructure and mechanical properties of LAM titanium alloys. Traditional solution treatment, namely pre-treatment and solution treatment in $\alpha+\beta$ region followed by aging, has been proved to be optimum heat treatment for the conventional wrought near β titanium alloys [11,12]. However, the as-deposited LAM near β titanium alloys are commonly characterized by large prior β grains including columnar and equiaxed grains, intragranular ultrafine basket-weave microstructure and numerous continuous grain boundary α (α_{GB}), which are obviously different from the conventional wrought parts [13−15]. Due to these features, the LAM near β titanium alloys often show higher strength and disastrous lower ductility in comparison to the corresponding wrought parts and cannot meet the requirements for engineering applications [13,14,16].

Because the microstructures of LAM titanium alloys are quite different from the wrought parts, the effect of traditional solution treatments might also be completely different from those on wrought parts [17,18].

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Therefore, studying the method to optimize the microstructure and obtain better mechanical properties by heat treatments is very significant for LAM near β titanium alloys. However, very little work has been done until now since most studies related to the LAM titanium alloys were focused on the $\alpha+\beta$ titanium alloys especially for the Ti−6Al−4V [7,9,19−22]. LIU et al [16,23] found that the continuous α_{GB} with the accompanying precipitate free zone (PFZ) is the main reason for the low ductility of LAM TC18 since the crack prefers to nucleating and propagating along the α_{GB}, resulting in intergranular fracture. And they found that the subtransus triplex heat treatment had better effect on the breakage of continuous α_{GB} and the improvement of ductility compared to the standard treatment despite of its narrow temperature window. In addition, according to the knowledge of the wrought titanium alloys, heat treatment in the single β region even for short time will inevitably lead to noticeable increasing of prior β grains and decreasing of mechanical properties [12,24]. However, it was reported that, unlike the $\alpha+\beta$ titanium alloys, the LAM near β titanium alloy showed no obvious grain growth behavior during heating in the single β region (about 15 °C above the β transus temperature) even for 0.5 h, possibly due to its good high temperature stability or original large prior β grains [25,26]. This result indicated an alternative heat treatment for the LAM near β titanium alloys to change the microstructures and mechanical properties.

In this study, the LAM TC17 titanium alloys were annealed in standard $\alpha+\beta$ region and single β phase region and further solution and aging treated in an attempt to investigate the effect of annealing temperature on the microstructure evolution and tensile mechanical properties. The attention was paid to the changing of the continuous α_{GB} and the PFZ and the effect on the tensile properties.

2 Experimental

A thick plate of TC17 alloy with a geometrical size of 300 mm × 200 mm × 35 mm was fabricated by laser additive manufacturing process using a 8 kW laser additive manufacturing system in an argon purged processing chamber with an oxygen content less than 60×10^{-6}. Spherical powders with a particle size ranging from 45 to 212 μm were used as the raw materials, which were produced by plasma atomization process. The laser deposition processing parameters were listed as follows: laser nominal output power 6 kW, laser beam diameter 6−7 mm, beam travel speed 1000 mm/min, powder feed rate 800−1000 g/h. The β transus temperature (T_β) of the as-deposited TC17 sample was (895±5) °C, determined by metallographic method.

12 specimens with a geometric size of 25 mm × 25 mm × 20 mm were machined by electric discharge wire cutting from the plate-like sample, and numbered from 1 to 12, respectively. Firstly, as shown in Table 1, Samples 1−6 and 7−12 were annealed at 840 and 910 °C for 1 h followed by air cooling, respectively. Then, Samples 2−6 and 8−12 were further solution-treated by holding for 0.5, 1, 2 and 4 h at 800 °C, respectively. Finally, on the basis of annealing and solution, Samples 6 and 12 were aged at 630 °C for 8 h. Longitudinal metallographic specimens were prepared by standard mechanical polishing and etched in a mixture solution of HF: HNO_3: H_2O with a volume ratio of 1: 6: 43. An OLYMPUS BX51M optical microscope (OM) and a Camscan 3400 scanning electron microscope (SEM) were used to observe the microstructure and fractography.

Table 1 Heat treatment details for LAM TC17 alloys

Sample No.	Heat treatment		
	Annealing	Solution	Aging
1	(840 °C, 1 h)+AC	−	−
2	(840 °C, 1 h)+AC	(800 °C, 0.5 h)+WQ	−
3	(840 °C, 1 h)+AC	(800 °C, 1 h)+WQ	−
4	(840 °C, 1 h)+AC	(800 °C, 2 h)+WQ	−
5	(840 °C, 1 h)+AC	(800 °C, 4 h)+WQ	−
6	(840 °C, 1 h)+AC	(800 °C, 4 h)+WQ	(630 °C, 8 h)+AC
7	(910 °C, 1 h)+AC	−	−
8	(910 °C, 1 h)+AC	(800 °C, 0.5 h)+WQ	−
9	(910 °C, 1 h)+AC	(800 °C, 1 h)+WQ	−
10	(910 °C, 1 h)+AC	(800 °C, 2 h)+WQ	−
11	(910 °C, 1 h)+AC	(800 °C, 4 h)+WQ	−
12	(910 °C, 1 h)+AC	(800 °C, 4 h)+WQ	(630 °C, 8 h)+AC

Room temperature tensile properties were tested according to the testing standard of ISO 6892−1:2009 at the National Analysis Center for Iron & Steel of China. The tensile specimen was dog-bone with a gauge diameter of 5 mm and a gauge length of 25 mm. All specimens were along deposition direction and located in the middle of the LAM plate-like sample. Three samples of each condition were tested for an average to reduce the measuring error.

3 Results

3.1 Microstructures

3.1.1 As-deposited alloy

The microstructures of as-deposited LAM TC17