



The influences of anneal temperature and cooling rate on microstructure and tensile properties of laser deposited Ti–4Al–1.5Mn titanium alloy



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ABSTRACT

As a metal near-net-shape manufacturing technology, direct laser fabrication has a great potential to reduce costs and delivery time and received an intense attention in the field of titanium alloy aerospace components fabrications. However, the laser deposited titanium alloys usually have equivalent strength and lower ductility compared to the wrought counterparts due to their lamellar microstructure. To investigate the responses of laser deposit titanium alloy Ti–4Al–1.5Mn to anneal parameters, various anneal temperatures and cooling rates were applied in this study. Microstructures were examined by Optical Microscope (OM) and Scanning Electron Microscope (SEM). Microhardness test and room temperature tensile tests were employed to evaluate the tensile properties of the as-deposited and annealed specimens. Results show that air cooling from the $\alpha + \beta$ phase region generates a microstructure composed of coarse primary α plates and fine lamellar transformed β , while water quenching produces similar but much finer microstructure. Moreover, higher cooling rate generates more area fraction of fine transformed β . With increasing anneal temperature, the ultimate tensile strength and yield strength increase for both cooling methods. Moreover, higher cooling rate leads to higher strength as expected. It is worth noting that both the strength and ductility of the laser deposited alloy improved by water quenched from the $\alpha + \beta$ duplex phase region. The improved tensile properties were mainly owing to the fine lamellar transformed β in the special bimodal microstructure.

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1. Introduction

Direct laser fabrication of titanium aerospace components has drawn much attention since 1990s, because its potential to reduce the buy to fly ratio and delivery time [1–4]. As a laser aided layer additive manufacturing technology, several processes, such as laser engineered net shaping (LENS), direct laser fabrication (DLF), direct metal deposition (DMD) and laser melting deposition (LMD), derived from laser rapid prototyping or laser cladding [1,5–9]. In laser melting deposition process, high power laser is controlled to melt and deposit the coaxially fed metal powders layer by layer to fabricate full dense and high performance components from their computer aided design (CAD) models. It has been successfully used to fabricate titanium alloys, TiAl alloy, Ti/TiAl structural gradient materials and titanium matrix composites [9–12].

However, laser deposited titanium alloys usually have equivalent strength and lower ductility than the wrought

counterparts due to their lamellar microstructure [13–15]. To alter the mechanical properties of laser deposited titanium alloy, heat treatments were applied in several studies. Generally, annealing at relatively low temperature, for example in the region of 550–750 °C, was performed to relieve the internal stress of the laser deposited titanium alloys. Anneal at higher temperature followed with lower cooling rates such as air cooling or furnace cooling usually promoted the ductility and depressed the strength of the laser deposited titanium alloy. Dinda et al. [15] reported annealing at 950 °C or 1050 °C followed with either air cooling or furnace cooling improved the ductility and reduced the strength of laser deposited Ti–6Al–4V, owing to their coarse and uniform annealing microstructures, and air cooling produced higher strength and lower ductility than that of furnace cooling. Similar results also reported by Zhang et al. [16]. In addition, Zhang et al. found that solution treated at temperatures below or above β -transus temperature followed with water quenching and aging enhanced strength and deteriorated ductility of laser deposited Ti–6Al–4V. However, in a study on laser deposited Ti–6Al–2Sn–4Zr–6Mo (Ti–6246), solution treated at 870 °C and aged at 595 °C depressed tensile strength of the alloy demonstrated by Blackwell and Wisbey [17]. Xie et al. [18] reported that both the tensile strength and ductility of laser

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deposited TA15 (Ti–6Al–2Zr–1Mo–1V) titanium alloy decreased with increasing anneal temperature in the $\alpha + \beta$ phase region. The previous studies indicate that heat treatment may be an effective method to improve the mechanical properties of laser deposited titanium alloys, but further study is still needed.

Ti–4Al–1.5Mn is a near- α titanium alloy with moderate strength (ultimate tensile strength ≥ 685 MPa). It is usually used as pipelines, skins and engine stators in aircrafts. There is about 4–6% β in the microstructure of the annealed commercial forged alloy. Due to its moderate aluminum and low molybdenum equivalent, the alloy is usually considered to be not heat-treatable [19–21]. Nevertheless, the microstructure features such as volume fraction and the morphology of primary α and transformed β of the alloy can be altered by heat treated in the $\alpha + \beta$ phase region, which has been demonstrated in the authors' previous research [22]. To further investigate the responses of laser deposited Ti–4Al–1.5Mn alloy to anneal parameters, various anneal temperatures and cooling rates were selected to change the volume fraction and morphology of α and transformed β , and room temperature tensile test was employed to evaluate mechanical performance of the annealed alloy. The effects of microstructure features such as volume fraction and width of primary α laths on tensile property of the alloy were investigated and discussed.

2. Experimental procedures

Laser melting deposition (LMD) process was conducted in a specifically designed Ar-purged processing chamber and the oxygen content of the atmosphere was kept less than 80 ppm. Spherical powders with a particle size ranging from 45 to 420 μm were used as the additive raw materials. The powders were produced by vacuum non-contacting plasma melting/gas atomization process. A 3 mm thick and sandblasted hot-rolled Ti–4Al–1.5Mn plate was used as the substrate. The LMD processing parameters were as follows: laser power 4500 W, laser beam diameter 5 mm, scanning speed 10 mm/s and powder delivery rate 100 cm^3/h . Plate-like sample with a geometric size of $30 \times 220 \times 195$ mm (without substrate) was fabricated by the laser melting deposition process. The details of the laser melting deposition process can be found in another paper [22].

The β transus temperature (T_β) of the laser deposited Ti–4Al–1.5Mn alloy was 970 °C [22]. Annealing at 927 °C, 945 °C, 955 °C and 965 °C (in the $\alpha + \beta$ phase region) for 0.5 h followed by either air cooling (AC) or water quenching (WQ) were applied to the laser deposited Ti–4Al–1.5Mn alloy. A stabilized anneal at 560 °C for 2 h followed with air cooling was performed as final treatment for the water quenched specimens (hereafter referred as water quenched specimen). The laser deposited alloy stress-relieving at 720 °C for 2 h followed by air cooling was taken as the reference materials (hereafter referred as as-deposited alloys). The schematic ternary phase diagram of Ti–4Al–Mn and selected anneal temperatures are shown in Fig. 1.

All the heat treatment procedures were performed in an electric-resistance furnace in air. The oxidation scale was no more than 1 mm thick according to microstructure observation and no less than 2 mm for each side was machined off before specimen preparation for XRD, metallographies and tensile tests. Phase identification for the samples of the as-deposited alloy and the alloys heat treated at 945 °C were carried out via X-ray diffraction with Cu K α radiation. Metallographic specimens were prepared by standard method and a universal Kroll's etchant of 1HF: 2HNO $_3$: 17H $_2$ O (vol. %) was used for etching. The microstructures of heat treated specimens were characterized by Optical Microscope (OM) (Olympus BX51M) and Scanning Electron Microscope (SEM) (KYKY-2800). A commercial metallographic image analysis software SISC IAS v8.0 was employed for quantitative metallography. The primary α area fractions for heat treated specimens were measured on optical microscope photos with a magnification of 200 and at least five photos were used for each condition.

Microhardness was measured on the surface of metallographic specimens using a MH-6 semi-automatic Vickers tester with a test load of 50 g and a dwell time of 10 s. At least five indents were made on the etched surface of each test specimen and the result is reported as the average value in the form of average $\pm$ standard deviation. For the microhardness measurements of the transformed β , indents were carefully made to make sure that the indentations were within the transformed β phase zones.

Room temperature tensile test was performed at National Analysis Center for Iron and Steel (China) using standard cylindrical bar specimens with gauge diameter of 5 mm and gauge length of 25 mm according to GB/T228–2002 (which is equivalent to ISO 6892–1: 1998). The tensile axis of all the specimens was parallel to the deposition direction and three specimens were tested for each condition to ensure the reproducibility of the results.

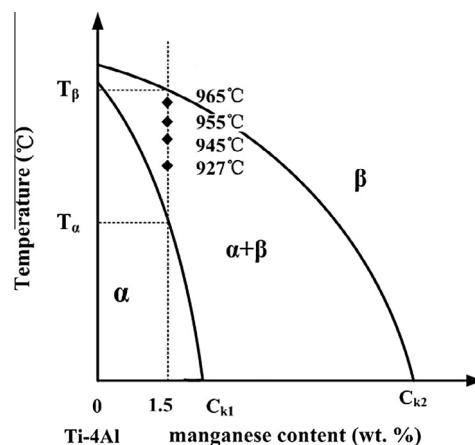


Fig. 1. Schematic ternary phase diagram Ti–4Al–Mn and selected anneal temperatures.

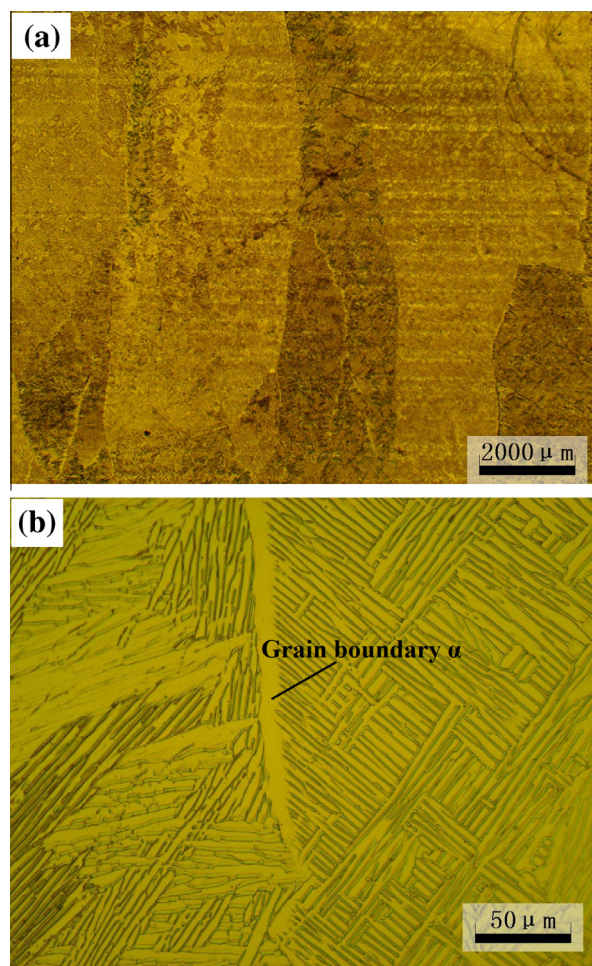


Fig. 2. OM micrograph showing microstructure of as-deposited Ti–4Al–1.5Mn alloy: (a) β grains and (b) lamellar microstructure.

3. Results and discussion

3.1. Microstructure

Fig. 2 shows the optical micrographs of the as-deposited Ti–4Al–1.5Mn alloy. The as-deposited alloy was Widmannstätten structure with α lath and no more than 10% of β lamellae. There were fair large columnar prior β grains (Fig. 2(a)) and relative small α colonies (Fig. 2(b)) in the microstructure of as-deposited alloy.

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