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Microstructure evolution and layer bands of laser melting deposition Ti–6.5Al–3.5Mo–1.5Zr–0.3Si titanium alloy

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ABSTRACT

Laser melting deposition (LMD) is a newly developed additive manufacturing technique which offers a potential of time and cost savings for fabricating aerospace titanium alloys components. In this paper, the grain morphology, microstructure and micro-hardness of LMD Ti–6.5Al–3.5Mo–1.5Zr–0.3Si titanium alloy were investigated. A variety of microstructures and two kinds of distinct layer bands were found in the as-deposited sample. The interlayer bands (ILB) spaced uniformly in the whole sample. However, the dark heat affected bands (HAB) with a special bimodal microstructure were absent in the last three layers. In order to obtain a deep understanding on the microstructure evolution and bands structure, much attention was paid on the microstructures of the last deposited several layers. The microstructure gradient between two HAB was due to the re-heating effect in the $\alpha + \beta$ region. The formation of interlayer bands was due to the chemical composition homogenization difference within and between ILB, which resulted from the superheating effect.

1. Introduction

Titanium alloys, especially $\alpha + \beta$ classification, are widely used in aerospace industry as key structural components due to their comprehensive combination of mechanical properties including high specific strength, good fracture toughness and excellent corrosion resistance [1–3]. However, the conventional wrought base processes of these components often involve a series of hot working steps and machining procedures, which inevitably results in great increasing of buy to fly ratio and lead time for production. The rapidly developing additive manufacturing techniques provide a potential approach to solve the problems [4–6].

Laser melting deposition (LMD) is one of the advanced additive manufacturing techniques that allow direct fabrication of full density near-net-shape metal components without die [6–8]. During LMD process, a high power laser is focused on the substrate to create a melting pool into which the powder feedstock is delivered through an inert gas flowing. The working table moves along a certain path defined by the CAD file of the component. The ejected powder particles are melted and solidify into component layer by layer, in a single-track way for thin wall and multi-track way for thick wall [6–9]. The LMD process is particularly appealing for manufacturing aerospace titanium alloy components because it can significantly reduce the cost and production time in comparison to traditional wrought base techniques [4,6]. Moreover, due to the additive and layer-wise production, it is even capable of producing some large complex components which cannot be obtained by conventional routes [10]. Accordingly, many studies have been carried out to investigate the LMD titanium alloys.

Previous reports related to LMD titanium alloys have included most commercial titanium alloys from α classification to β classification, though most of the attention was paid to the Ti–6Al–4V (TC4) [4–7,11–22]. Generally, due to the large temperature gradient and rapid solidification rate during the process, the LMD titanium alloys are typically characterized by large prior columnar β grains with ultrafine basket-weave microstructure. During the LMD process, the thermal effect on the previous deposited layers executed by the melting pool, plays an important role on the formation of final microstructure [8,12,16,23]. Kelly and Kampe studied the microstructure of the LMD TC4 and figured out that the melting pool would re-heat the last two deposited layers into single β region and the third layer to $\alpha + \beta$ region [16]. Liu et al. studied the microstructure evolution process of LMD TC18 [8,12]. These few literatures have pointed out some basic principles, however, the existing results are insufficient to clearly understand the microstructure evolution process. In addition, regularly distributed layer bands is another obvious symbol of LMD titanium alloys. Although many authors have observed the layer bands

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[8,14,16,23–28], it should be pointed out, that few researchers studied the formation mechanism of the layer bands [8,16]. For example, Kelly and Kampe thought that layer band of LMD TC4 sample formed in the N layer when the $N + 3$ layer was being deposited due to the absence of layer band in the last three layers [16], whereas Liu et al. found that the layer band existed even in the last layer in the LMD Ti–5Al–5Mo–5V–1Cr–1Fe (TC18) [8]. However, with regard to the specific formation mechanism, no agreed results have been obtained. Moreover, the previous theories cannot well explain the latest experimental results. To the authors' knowledge and as will be discussed in this paper, two kinds of totally different bands exist in most LMD titanium alloys and the formation mechanisms are also different. However, the previous reports did not distinguish them clearly. To make clear these basic problems can help us have a deep understanding on the LMD process.

In this paper, laser melting deposited Ti–6.5Al–3.5Mo–1.5Zr–0.3Si (named TC11 in China and BT9 in Russia) titanium alloy was chosen for the investigation. Firstly the macro- and microstructures of different regions were studied. Then much attention was paid on the microstructure features of the last deposited several layers. At last, the microstructure evolution process was analyzed in detail and the formation mechanism of layer bands was discussed.

2. Materials and experimental procedures

2.1. Laser melting deposition

An in-house developed laser melting deposition system was used to fabricate plate-like samples. The LMD system is equipped with a GS-TFL-8000 CO2 laser (maximum output power 8 kW), a BSF-2 power feeder together with a co-axial powder delivery nozzle, a HNC-21M computer numerical control multi-axis motion system, and an argon purged processing chamber with oxygen content less than 100 ppm. The LMD processing parameters were as follows: laser power 4–6 kW, laser beam diameter at melting pool 4–6 mm, laser scanning speed 800–1200 mm/min, powder feed rate 600–1000 g/h, and layer thickness 1–1.5 mm. The LMD process was schematically shown in Fig. 1. The raw powders were produced by plasma atomization, with the particle size mainly from 100 to 300 μm. Under these parameters, a TC11 plate was fabricated with a geometry size of 300 mm × 200 mm × 30 mm.

2.2. Microstructural characterization

After LMD process, cubic specimens were cut from the as-deposited plate for microstructure observation. If not specially indicated, all the samples in this research were observed from the front view (YOZ section), as shown in Fig. 1. One heat-treated sample (HT sample) was prepared for the discussing by solution treatment at 1005 °C for 1 h follow by quenched into water. Metallographic specimens were prepared by standard mechanical polishing and etched in a mixture solution of HF:HNO_3:H_2O with a ratio of 1:6:43. The microstructure was examined by Olympus BX51M optical microscope (OM) and Cambridge-S360 scanning electron microscope (SEM). A commercial metallographic image analysis software ImageJ was employed for quantitative metallography. Cubic samples were cut from the unstable zone, stable zone and HT sample and prepared with the testing section perpendicular to the deposition direction for phase identification by X-ray diffraction (XRD) testing. The XRD was conducted by Dmax-2200pc automatic diffractometer with Cu target Kα radiation. Micro-hardness was measured by a HAZ-1000 semi-automatic Viker tester with a test load of 300 g and a dwell time of 15 s.

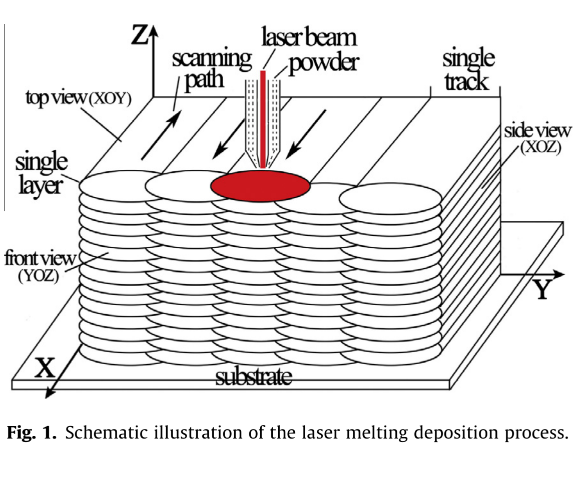

Fig. 1. Schematic illustration of the laser melting deposition process.

3. Results and discussion

3.1. Macrostructure

Fig. 2 shows the macrostructure of the as-deposited TC11 sample. There exist two distinct zones in the sample: the unstable zone with darker contrast in the top region and the stable zone with brighter contrast in the bottom region. The height of the unstable zone is only about 3–4 mm. This is a common phenomenon in many additive manufactured titanium alloys [12,14,16,23,24]. The stable zone and the unstable zone exhibit the same special grain morphology of alternately arrayed columnar grains and equiaxed grains. These large prior β columnar grains typically traverse many layers, indicating an epitaxial growth towards the heat flux. However, the grain size range of the near equiaxed grains is only about 50–200 μm. The detailed characteristic and formation mechanism of the special grain morphology has been deeply discussed in [9]. Regularly distributed layer bands can be faintly observed in the stable zone. However, no one exists in the unstable zone.

3.2. Microstructure characteristics

Fig. 3 shows the OM images of the stable zone of as-deposited TC11 sample. The existence of two kinds of distinct bands is an important feature that can be discerned. One is the wide dark curved bands indicated by black arrows in Fig. 3, which are called heat affected bands (HAB) in this paper. The other is the narrow cambered bands marked by white arrows, which are named interlayer bands (ILB). It is very interesting to note that the ILB can be observed more clearly for differential-interference mode (Fig. 3b) in comparison with the bright field mode in which the ILB are difficult to discern (Fig. 3a). This may suggest that the ILB are not in the same horizontal plane, which probably formed in the etching process. In compared with the HAB, the ILB are spaced more evenly throughout the whole stable zone, about 750 μm apart which is almost the same value with the Z increment in LMD process. There seems no regular relationship between the two kinds of bands. Some of them are parallel and some are even intersecting.

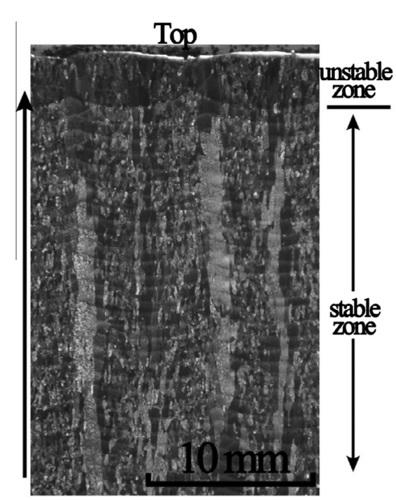

Fig. 2. Macrostructure of the as-deposited TC11 sample (the left black arrow indicating the depositing direction).