



Grain morphology evolution behavior of titanium alloy components during laser melting deposition additive manufacturing



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ABSTRACT

Grain morphology control is a challenging issue for laser melting deposition (LMD) additive manufacturing of large metallic components. In this paper, the grain morphology evolution behaviors of laser deposited titanium alloy components were investigated via basic study on solidification nucleation and growth mechanisms of the local melt pool during the layer-by-layer deposition process. Results indicate that the heterogeneous nucleation on partially melted powders for equiaxed grains and the epitaxial growth from the pool-bottom for columnar grains are the two dominant solidification mechanisms. The competition between the above two solidification mechanisms within the melt pool dominates the grain morphological selection process and determines the as-deposited grain structures for the layer-by-layer deposited components. Low specific mass deposition rate leads to high superheating of the melt pool, large melting penetration to the underlying layer and high temperature gradient in front of solidification interface, making the bottom epitaxial growth mechanism prevail and promoting the formation of large full-columnar prior grain structures. While high specific mass deposition rate results in insufficient powder melting and low melt superheating, making superficial and endogenous heterogeneous nucleation within the melt pool prevail, favoring the production of fine near equiaxed prior grains. Other than the full-columnar and equiaxed as-deposited grain structures, a unique “steel-bar reinforced concrete-like” mixed grain structure consisting of coarse grain pillars and fine inter-pillar equiaxed grains was fabricated and the corresponding grain morphology selection mechanisms for the three representative as-deposited grain morphologies were established.

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1. Introduction

Applications of titanium alloys in the aviation industries as large and critical load-bearing structural components such as bulkheads in modern civilian and military airliners and integrally bladed disks (blisks) in advanced gas turbine engines, are ever increasing because of their excellent combination of low density, high specific strength, excellent elevated-temperature mechanical properties, exceptional corrosion resistance and good compatibility to polymer matrix composites [1–3]. However, titanium alloys are also well-known for their poor materials-processing and components-manufacturing abilities compared to other metallic structural materials such as iron, aluminum and nickel-base alloys, owing to their inherent physical and chemical properties such as

high yield strength, low strain-hardening exponent, low thermal conductivity, and high friction coefficient and high chemical activities [2,4]. Manufacturing of large aeronautical titanium structural components by the wrought-based traditional advanced manufacturing processes has been recognized both technologically difficult and economically expensive [5–9].

Laser additive manufacturing (LAM) based on coaxial powder-delivery melting/rapid solidification layer-upon-layer deposition for fully dense near-net-shape metallic components directly from CAD (computer aided design) files is a revolutionary materials-processing integrated digital manufacturing process [5–8,10–13]. It is both technologically advantageous and economically competitive to manufacture those high-performance large and critical components made of difficult-to-process metallic or inter-metallic materials like titanium alloys, because of its many unique merits over conventional manufacturing processes, e.g., no tooling, few materials waste and post-deposition machining, high materials buy-to-fly ratio, short production cycle, low production cost, no restriction to component size and geometries, great flexibility to

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design changes, etc. The laser additive manufacturing technology has attracted increasing and world-wide attentions since middle 1990s and a series of technologies with the same principles but different names have been developed, such as Laser Engineered Net Shaping (LENS) by the Sandia National Laboratories [14–16], Directed Light Fabrication (DLF) by the Los Alamos National Laboratories [17,18], the Direct Metal deposition (DMD) by the University of Michigan [19,20], Laser Powder Deposition (LPD) by the Fraunhofer Laser Technology Institute [21,22], and laser melting deposition (LMD) by the Beihang University (China) [8,23–26].

Particular research activities on laser melting deposition additive manufacturing technology in the past three decades have focused on near-net-shaping of aircraft titanium critical structural components aiming for superior internal metallurgical quality and mechanical performances [8]. The as-deposited prior beta grain structure is recognized to be one of the most important structural factors governing mechanical properties for the layer-by-layer additively built-up titanium components. The as-deposited grain size and grain morphologies, post-deposition heat treated microstructure as well as mechanical properties of laser deposited titanium components have been extensively investigated [7,27–33]. The titanium alloys components made by whether powder-delivery or wire-feed additive manufacturing were reported to have the inherent features of strong solidification textures characterized by large prior beta columnar grains aligning along the build-up directions as a result of the strong epitaxial growth conditions for the parent grains at pool-bottom during rapid solidification with high temperature gradient conditions [11,20,27,28,32,34–36]. The tensile properties and impact toughness were observed to exhibit notable anisotropy with generally lower tensile strength, and better tensile ductility and impact toughness in the build-up direction than that of the transverse direction [29,31,32]. Moreover, titanium-based gradient structural materials (GSMs) components fabricated by the laser melting deposition additive manufacturing process such as Ti–6Al–4V/Ti–6.5Al–3.5Mo–1.5Zr–0.3Si, Ti/Ti–6.5Al–2Zr–1Mo–1V, and Ti–48Al–2Cr–2Nb/Ti–6.5Al–2Zr–1Mo–1V, were also reported to have the directionally aligned columnar grains along the deposition directions [37–39].

However, diversities in prior beta grain morphologies were recently observed in a series of laser melting deposited components in both near-alpha, alpha + beta and near-beta titanium alloys. A “bamboo-like” mixed grains consisting of coarse short-column or olive-like grain arrays and inter-array fine equiaxed grains was reported along the build-up direction in laser deposited near-beta Ti–5Al–5Mo–5V–1Cr–1Fe and Ti–5Al–2Sn–2Zr–4Mo–4Cr alloys [40,41]. An alternatively arranged columnar and equiaxed mixed grains in the transverse directions were achieved in a laser deposited Ti–6.5Al–3.5Mo–1.5Zr–0.3Si structural components under certain process parameters [42,43]. However, the proposed hypotheses or explanations for the diverse prior beta grain morphologies were lack of supporting of actual experiments and seems limited [40–43].

Establishing a feasible grain morphology control method for laser melting deposition additive manufactured large titanium components is still a challenging question and needs more fundamental understandings on solidification behaviors during layer-upon-layer laser additive manufacturing process. As a layered built-up manufacturing process, the solidification nucleation and growth behaviors of the local melt-pool have profound effect on grain structures of the final deposited components. In the present paper, the typical alpha + beta titanium alloy with nominal composition (wt.%) of Ti–6.5Al–3.5Mo–1.5Zr–0.3Si (named TC11 in China and BT9 in Russia), which was widely applied in both aircrafts and aero-engines as critical structural components due to its excellent comprehensive mechanical properties at room and elevated temperature up to 500 °C, was selected as the experimental material.

The TC11 alloy has a medium alloying extent with the Mo equivalence of 3.5 and thus the following research results should have an important reference value on the other $\alpha + \beta$ titanium alloys. Single-track laser melting deposition experiments were conducted to investigate the solidification nucleation and growth mechanisms of the laser induced local melt pool as functions of mass deposition rate while all the other laser deposition processing parameters including laser power, beam diameter and beam scan rate are kept constant. The as-deposited grain structures and grain morphological selection behaviors of a layer-by-layer deposited titanium alloy component were then comprehensively studied based on local melt pool solidification mechanisms, aiming to establish a general method for grain morphology control for laser additive manufactured titanium components.

2. Experimental procedures

The additive manufacturing experiments was carried out in a LMD-V laser melting deposition additive manufacturing system having a maximum component manufacturing capability of 4000 mm × 3000 mm × 2000 mm, developed at the National Engineering Laboratory of Additive Manufacturing for Large Metallic Components, Beihang University. The system consists of a 10 kW fiber coupled diode laser with a beam wavelength of 980–1020 nm, a 4-axis mechanical work station, an argon-purged deposition chamber, a coaxial powder delivery and powder/laser coupling system, a process monitoring unit and a computer numerical control (CNC) unit for the whole system. The argon atmosphere within the laser melting deposition chamber during laser melting deposition was kept constant with an oxygen content less than 80 ppm. Spherical powders with a particle size ranging from approximately 80 μm to 250 μm (as shown in Fig. 1) produced by the plasma rotating electrode process (PREP) were used as the raw material for the laser melting deposition additive manufacturing process.

In order to investigate the solidification nucleation and growth mechanisms of the local melt pool and hence providing the foundation for analyzing solidification grain morphology evolution during layer-by-layer laser melting deposition process, a set of single-track and single-layer laser melting deposition experiments were firstly conducted with varying mass deposition rates of 6, 11, 15, 20, 25, 31, 36, 44, 55 and 59 g/min, respectively, while all the other processing parameters are kept constant at laser power 6 kW, beam diameter 6 mm, overlapping ratio 40–50% and beam scanning speed 1000 mm/min. To eliminate the interference of parent grain growth at the pool bottom on the solidification behaviors during laser melting deposition manufacturing process, thick plate-like specimens of the same titanium alloy produced by laser melting deposition manufacturing process having a coarse mixed prior beta grain structure (as indicated in Fig. 2) was selected as the substrate. Because the as-deposited beta grains were demonstrated to have excellent high-temperature structural stability, suffering no notable grain growth during short-term high-temperatures exposures up to melting because of the inherent low grain boundary energy compared to forged counterparts [44]. Transverse (perpendicular to beam scanning direction) cross sections of laser deposited specimens were prepared by the conventional metallographic method and were etched in HF–HNO₃–H₂O water solution in volume proportion of 1:6:43. The as-deposited grain morphologies were characterized with a Leica DM4000 optical microscope. Then the area fractions of equiaxed and columnar grains, f_{EG} and f_{CG} , the maximum depth of equiaxed grain layer d_{EG} , and the remelting depth to the underlying layer

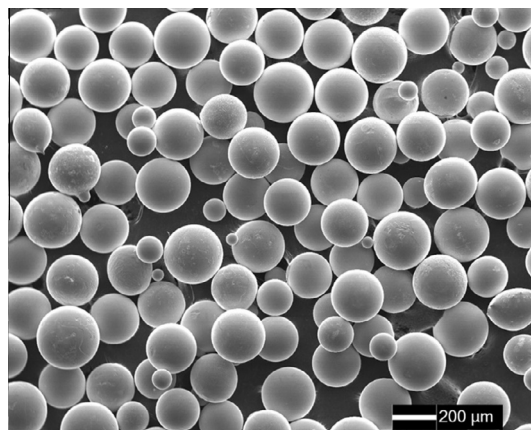


Fig. 1. SEM micrograph showing the spherical powders of the TC11 alloy prepared by PREP process.

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