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Grain morphologies and microstructures of laser melting deposited V-5Cr-5Ti alloys

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ABSTRACT

A laser melting deposition (LMD) technique has been applied to fabricate thin wall V-5Cr-5Ti samples. By applying a scanning speed of 400 mm/min, laser powers of 1200W, 1400W, 1600W, and 1800W, and scanning strategies of single directional scanning and dual directional scanning, full dense thin wall samples have been successfully prepared. Microstructures at the bottom region of walls mainly consist of coarse columnar grains, showing a ⟨100⟩ fiber texture. Microstructures in the middle and at the top regions of walls mainly consist of fine columnar grains or equiaxed grains, showing random textures. Columnar dendritic growth takes place for columnar grains. The columnar dendrites grow epitaxially from parent grains, following one [100] axis closest to the heat flux direction. However, the integral growth directions of columnar grains are opposite to the heat flux direction. Including a small deviation of one [100] axis from heat flux direction, the growth space of columnar dendrites also counts for the success in competitive growth for columnar grains. Deposition height, laser power, and scanning strategy show significant effects on the grain structure evolutions of thin wall samples, due to their effects on the temperature gradient. As the deposition height increases, columnar to equiaxed transitions (CETs) have been observed for all samples. The CETs happen faster for higher laser power, and for dual directional scanning compared to single directional scanning. Due to the differences in local composition caused by microsegregation, clusters containing lath-like precipitates are observed to delineate the dendrites. The effects of processing parameters on microstructures can be represented by a metric of volumetric energy density. A decrease of energy density will lead to CETs.

1. Introduction

Vanadium alloys have been considered as promising candidates as structural materials for fusion reactors, due to many unique properties such as superior high temperature strength, low activation characteristics, resistance to severe radiation, chemical inertness in liquid metal systems [1–3]. The preparation processes, microstructures and properties of V-(4–5)Cr-(4–5)Ti alloys have been widely explored for the applications in nuclear systems [4–11]. Traditional methods to prepare V-(4–5)Cr-(4–5)Ti alloys mainly include melting/wrought-based processes and powder metallurgy processes [12–15]. However, these processes are often costly and time-consuming.

Recently, a laser melting deposition (LMD) additive manufacturing technique has attracted extensive interest for the preparation of near net shaped components with high performance. This technique combines laser cladding and rapid prototyping, offering advantages of time saving, single-step fabrication, and materials waste-free [16]. The LMD technique has been widely used in the preparation of titanium alloys [17–20], superalloys [21–23], steels [24,25], and aluminum alloys [26,27] et al. Moreover, products manufactured using LMD process can show mechanical properties that are equivalent or superior to the wrought counterparts [28,29]. Thus, LMD is particularly attractive for the fabrication of high valued vanadium components.

In this work, the LMD technique has been used for the preparation of thin wall V-5Cr-5Ti samples. Effects of process parameters such as laser power and scanning strategy on the grain morphologies and microstructures of the deposited alloys are investigated.

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2. Experimental

Raw materials were V-5Cr-5Ti alloy powders prepared using plasma rotating electrode process. The powders have a spherical shape (as shown in Fig. 1), and a mean powder size of approximately 200 μm measured using a Microtrac S3500 laser particle size analyzer. Powders were dried by heating up to 80 °C for 2 h, and then cooled down to room temperature in a vacuum chamber before use. To eliminate the stress caused by different thermal coefficient between deposits and substrates, vanadium alloys with the same nominal composition of V-5Cr-5Ti, prepared using powder metallurgy process, were chosen as substrates.

The laser melting deposition experiments were carried out in a laser additive manufacturing system having a maximum component manufacturing capability of 800 mm × 700 mm × 600 mm. The system is equipped with an ytterbium doped fiber laser (1070 nm wave length), a five-axes computer-numerical controlled work station, a chamber filled with high-purity argon gas, a coaxial powder delivery system, and a process monitoring unit. During the deposition process, the oxygen content in the chamber was controlled to be below 20 ppm. Powders were delivered into the chamber through a coaxial nozzle at a feeding rate of 7–9 g/min, under the protection of argon gas.

Thin wall samples with lengths of 60 mm, and heights of approximately 40 mm were designed to be built by multi-layer scannings. The height of the laser head was increased at a certain height increment after a single laser scan at each layer. The scanning direction for each layer can be the same (*i.e.* single direction) or opposite (*i.e.* dual direction) for the fabrication of walls. A wall (sample A) was first fabricated using single directional scanning, at a scanning speed of 400 mm/min, and a laser power of 1200W. However, the wall had an irregular shape, showing an accumulated height drop towards the end of each scan. Four wall samples were then fabricated using dual directional scanning under different laser powers. These samples show regular shapes. The process parameters for each sample are listed in Table 1.

Chemical compositions of raw materials and fabricated wall samples were measured using inductively coupled plasma atomic emission spectroscopy and oxygen, carbon and nitrogen content analyzer, and Table 2 shows the results. The impurity levels of samples are similar before and after LMD process, except for the increasing contents of iron, carbon and oxygen. The increases of iron and carbon are supposed to originate from the contamination of residual steel powders in the powder delivery system from a former LMD experiment. The increase of oxygen is supposed to originate from the absorption of oxygen from the atmosphere. This increased impurity of oxygen is huge for vanadium alloys. A stricter gas protection must be applied in the future work.

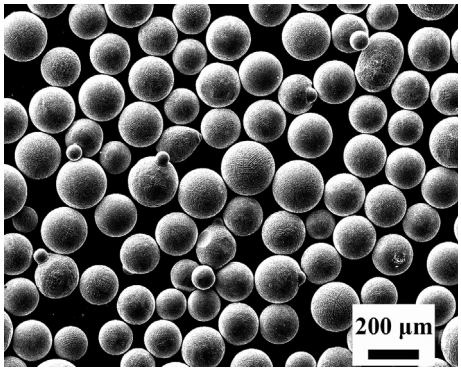

Fig. 1. Morphology of V-5Cr-5Ti alloy powders showing a spherical shape.

The walls were cut by spark erosion to observe microstructures in the cross-sections perpendicular to the laser scanning direction (SD), the deposition direction (DD), and the transverse direction (TD). Before observation, the cross sections were gridded, and then electropolished or corroded by standard metallographic procedures. The electropolishing was performed using a solution of 5 vol% sulphuric acid in water at the voltage of 5 V for 8 s. The corrosion was performed using a mixed solution of nitric acid, hydrofluoric acid, and water for 3 min. Microstructure and texture investigations were carried out using a SZ61 optical microscope and a Tescan Mira 3LMH scanning electron microscope, which equipped with an Oxford Instruments electron backscatter diffraction (EBSD) system. For all EBSD maps shown in this paper, only high angle grain boundaries (HAGBs, >10°) were drawn, and the colors of grains represented the crystal orientation in the direction parallel to DD. Only grains with an aspect ratio larger than 4:1 were considered as columnar grains.

3. Results and discussions

3.1. Grain morphology

The cross sections perpendicular to SD of samples A, B, C, D, and E were first observed using optical microscopy, as shown in Fig. 2. The deposition directions for all the five samples in Fig. 2 are from left to right. It is noticed that all the samples show dense structures without obvious pores or cracks. Dominations of columnar grains are observed at the bottom regions of all samples. These columnar grains have widths of 60–200 μm, and heights of 200–3000 μm. Columnar grains stop growing, and equiaxed grains start to grow as the deposition heights reach 11 mm, 5 mm, 2 mm, 3 mm, and 3 mm for samples A, B, C, D, and E, respectively. For samples A, C, D, and E, a uniform distribution of equaxied grains are observed in the middle and top regions. Grains at the top region show a much finer grain size compared to the middle region. For sample B, a combination of columnar grains and equiaxed grains are observed in the middle region. Columnar grains grow along the center line of sample. Equiaxed grains grow at the surface of sample. As the height increase, the columnar grains along the center line change into equiaxed grains, however, showing a much coarser grain size compared to the equiaxed grains at the surface. In general, the five samples all consist of columnar grains and equiaxed grains. As the height increases, columnar to equiaxed transitions (CETs) have been observed. The CETs happen faster for higher laser power, and for dual directional scanning.

3.1.1. Competitive growth

To understand the prevalence of columnar grains and the growth behavior of grains during multi-layer LMD process, detailed microstructural and crystallographic investigations on the cross section of a one-layer deposit were first carried out using both SEM and EBSD. Fig. 3(a) and (b) show example EBSD maps of typical grain morphologies in the cross section of a one-layer deposit. Fig. 3(c) shows the corresponding SEM image of the observed one-layer deposit. Grains identified using EBSD at the bottom part of molten pool are depicted with red color and numbered in the SEM image for help of better recognition. A solid/liquid interface between the substrate and the deposit is observed at the bottom of the molten pool as shown in Fig. 3(b) and (c). There are in total 23 grains along the interface, including 12 columnar grains and 11 near-equiaxed or equiaxed grains, as explicated in Table 3. These grains have the same crystallographic orientations of parent grains, indicating by the same colors with parent grains in Fig. 3(a). The uninterrupted crystallographic orientations confirm an epitaxial growth for LMD process.