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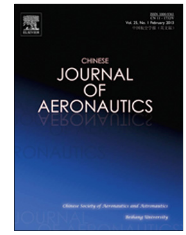

Single track and single layer formation in selective laser melting of niobium solid solution alloy

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Abstract Selective laser melting (SLM) was employed to fabricate Nb-37Ti-13Cr-2Al-1Si (at%) alloy, using pre-alloyed powders prepared by plasma rotating electrode processing (PREP). A series of single tracks and single layers under different processing parameters was manufactured to evaluate the processing feasibility by SLM, including laser power, scanning speed, and hatch distance. Results showed that continuous single tracks could be fabricated using proper laser powers and scanning velocities. Both the width of a single track and its penetration depth into a substrate increased with an increase of the linear laser beam energy density (LED), i.e., an increase of the laser power and a decrease of the scanning speed. Nb, Ti, Si, Cr, and Al elements distributed heterogeneously over the melt pool in the form of swirl-like patterns. An excess of the hatch distance was not able to interconnect neighboring tracks. Under improper processing parameters, a balling phenomenon occurred, but could be eliminated with an increased LED. This work testified the SLM-processing feasibility of Nb-based alloy and promoted the application of SLM to the manufacture of niobium-based alloys.

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1. Introduction

Refractory niobium-based alloys are promising materials for high-temperature structural applications, owing to the ultra-high melting point of Nb and their qualified high- and room-temperature mechanical properties.[1–3] As in situ composites, Nb-Si-based alloys combine Nb solid solutions (Nbss) with intermetallic compounds of Nb_5Si_3 and/or Nb_3Si to improve their strength and stiffness as well as oxidation resistance at very high temperatures.[2,4,5] Recent development on processing techniques has endowed Nb-based alloys with an improved performance. Meanwhile, it is known that the processing of Nb-based alloys by traditional subtractive manufacturing techniques requires complicated procedures and limited production efficiency. Moreover, thermodynamically stable and chemically inert mould materials are also needed for the manufacture of Nb-based alloys with high melting temperature and high reactivity.[6]

As a laser-based additive manufacture technology, selective laser melting (SLM) has gained considerable recognition since

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being introduced.[7,8] The distinguished benefits of SLM over traditional manufacturing techniques are highlighted as high production rate, design freedom, cost saving, and high utilization ratio of materials. Plenty of research efforts have been focused on the SLM-processing of Ti-based, Ni-based, Fe-based, and Al-based alloys.[8–11] Xia et al.[10] reported the fabrication of Ni-based superalloys by SLM and found that at an optimized linear energy density of 221.5 J/m, the outward convection favored the escapement of bubbles, resulting in a high relative density of 98.9%, but a higher linear energy density would increase the residual porosity and reduce the densification. Owing to the higher cooling rate during SLM, a finer microstructure tends to be achieved, and a higher hardness and compression strength as well as an improved wear resistance are normally obtained.[11] Furthermore, the SLM processing of refractory metals of tantalum[12] and tungsten[13] have been reported. Our previous work[14] investigated the manufacture of Nb-Si-based in situ composites by SLM, which consisted of Nbss and silicide phases, using irregular jet-milled powders.

Since SLM is a track-by-track and layer-by-layer process, the performance of a component built by SLM depends largely on the quality of each single laser-melted track and each single layer.[15–17] Sound tracks well bonded to a substrate or previous layer are required to obtain qualified components. A numerical model has been presented to predict single tracks in SLM, which allows for the effects of powder properties, scanning speed, laser beam absorption, and heat conduction.[16] Yadroitsev et al.[17] presented that there was a threshold characteristic corresponding to the fomentation of single tracks, and the stability of single tracks depended on the processing parameters. Instabilities, in forms of irregularities and distortions, were typically formed at a low scanning speed. Cheikh et al.[18] found that during the coaxial laser cladding process, single tracks were flattened with a high scanning speed and a low feed rate, and cylindrical tracks were formed at a low scanning speed and a high feed rate.

Since single-phase niobium solid solution alloys have not been fabricated by SLM previously, it is of importance to perform primary experiments focusing on single track and single layer formations. Pre-alloyed niobium solid solution alloy powders are processed in this work. The aim of this work is to clarify the characteristics of laser-melted tracks and the sectional melt pool (MP) under either proper or improper processing parameters.

2. Experimental

With a nominal composition of Nb-37Ti-13Cr-2Al-1Si (at%), pre-alloyed powders were prepared by plasma rotating electrode processing (PREP). Nb-based alloy disks, produced via vacuum induction melting (VIM), were used as electrodes for PREP. Powders with a size ranging from 45 μm to 75 μm were screened for SLM. As shown in Fig. 1, spherical Nbss pre-alloyed powders were fabricated by PREP. Those pre-alloyed powders were featured by smooth surfaces with the absence of oxide particles. Fine dendrite structures were observed on the powder surface, resulting from the large undercooling during PREP.

The SLM machine employed in this work was equipped with a fiber laser with a maximum power of 500 W. The intensity of the fiber laser beam exhibited a typical Gaussian distribution. The building chamber of the SLM machine was filled with Ar atmosphere to avoid any oxidation, and the oxygen content in the chamber was below 0.1 wt%. A computer system was designed to control the building process. Prior to laser scanning, a powder layer was spread on a titanium platform. The thickness of the powder layer was 80 μm. A series of single tracks and single layers was fabricated under different scanning speeds (V), laser powers (P), and hatch distances (D). The processing parameters of SLM are listed in Tables 1 and 2. The schematic of the SLM physical model is shown in Fig. 2(a). The zigzag scanning strategy was performed for single layer formation (Fig. 2(b)). The linear laser beam energy density (LED) is a critical factor that determines the melting and solidifying behaviors of powders, which is defined by the following equation:

$$\mathrm{LED} = P/V \tag{1}$$

Surface morphology observation was performed using a scanning electron microscope (SEM, JEOL JSM 6010). The sectional microstructures of single tracks and single layers were examined using an election probe microanalyzer (EPMA, JXA-8230). Elemental distribution images were obtained by wavelength dispersive X-ray spectrometers (WDS) attached to the EPMA. The ZAF-corrected EPMA was calibrated by pure standards for different operating conditions and probe sizes. Prior to sectional microstructure examination, samples were mounted with epoxy resin, grounded up to 1200# using metallographic abrasive papers, and finally mechanically polished on Fe_2O_3/CrO_3 impregnated cloths.

3. Results and discussion

Fig. 3 shows the typical surface morphologies of the first-layer single tracks under different scanning speeds and laser powers. The phenomenon that both continuous and discontinuous single tracks exist at each set of input parameters of laser power and scanning speed indicates that the morphology of single tracks depends largely on the processing parameters. With a laser power of 270 W and a scanning speed of 1200 mm/s, only several drops have been formed on the substrate. Under the given processing parameters, there are ten continuous tracks formed on the substrates. It is worth noting that the five tracks formed at 380 W are all continuous, with a scanning speed ranging from 200 mm/s to 1200 mm/s. It suggests that an increase in the laser power benefits the formation of continuous tracks. When producing SLM parts, only continuous tracks are desired, because this kind of tracks typically generate a sound bonding between adjacent tracks and a fully dense final part. The fragmentation of single tracks, i.e., a balling phenomenon, is also observed. It is an unfavorable drawback of SLM processing.[13,19,20] Remarkably, the balling phenomenon could be eliminated, by either decreasing the scanning speed or increasing the laser power (Fig. 3). However, intrinsically, both of them result in an increase of the LED.

During SLM, a laser beam-powder-substrate system is generated. A range of physical and chemical phenomena take place in the course of the melting and solidifying processes of powders, including absorption, reflection and heat transfer, phase transformation, fluid flow and mass transfer, and chemical reactions.[21–24] The mechanism of the elimination of the

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