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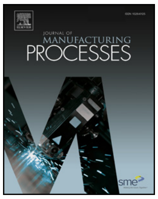

Metallurgical features of direct laser-deposited Ti6Al4V with trace boron

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ABSTRACT

The variation in the metallurgical characteristics, in terms of microstructure and microhardness, of direct laser deposited Ti6Al4V premixed with trace boron (0.04 wt%) was investigated. A significant improvement in the clad hardness from 390 to 450 HV in Ti6Al4V deposit to 510–600 HV in Ti6Al4V0.04B clad was observed. This was attributed to not only the fine α-Ti laths but also the presence of very hard TiB precipitates formed in the latter sample when compared to the martensitic α′-Ti formed in the former specimen. The high cooling rates experienced during deposition produced an extremely fine and even distribution of TiB.

1. Introduction

Direct laser deposition (DLD), also known as direct metal deposition (DMD), laser-engineered net shaping (LENS), laser cladding, etc., can be considered both as an additive manufacturing process as well as a surface modification technique, whereby either functional parts are fabricated using layer-by-layer building approach, or damaged components are repaired by cladding similar or different material onto a surface. In a DLD process, a laser is used to create a small melt pool on the surface of the substrate prior to introducing the cladding material either in powder or wire form, thereby binding the materials upon solidification. It is an economical technique for the fabrication of near-net shape parts with complex geometries or the repair of high-value components, thus finding applications predominantly in the defence, aerospace and biomedical industries [1,2]. Titanium is one such material highly desired for various applications in these industries owing to their superior inherent characteristics such as high strength-to-weight ratio, excellent corrosion resistance, and biocompatibility. For this reason, there has been considerable research on the additive manufacturability of titanium alloys considering the fact that in the aerospace industry the buy-to-fly ratio for titanium is typically at least 10:1 with more than 90% of the raw material being converted into waste machined swarf [3,4]. Irrespective of the manufacturing route of new titanium components, a common challenge is the low-cost repair and sustainment of worn or failed components. Depending on the application, some components are suited to undergoing repair when worn as complete replacement (and the associated costs) may be unnecessary, particularly in localised minor wear. DLD is one such technology well suited for this purpose [5,6]. Furthermore, the advantage is that such technologies can produce functionally graded repairs or repairs using different alloys that may be less susceptible to future degradation or wear or offer other improved surface properties. Gorunov [7] reported that DLD can effectively apply heat-resistant coatings and even complex claddings consisting of ceramics embedded in a titanium metal matrix onto worn and/or damaged titanium turbine blades. He also reported that the presence of high-temperature phases such as TiB and Ti_3Al in the coating is beneficial as they impart high hardness and subsequently improved wear resistance. Likewise, Nazari et al. [8] cladded a novel Ti-Fe composite coating onto a titanium substrate that displayed very high hardness in the range of 620–815 HV which is a promising repair solution for high-value titanium aircraft components.

One of the challenging factors of DLD cladding is the control of the solidified microstructure including promoting the formation of fine equiaxed crystals (grain refinement). Several studies have been reported on the grain refinement effect of boron addition during laser deposition of titanium alloys. Banerjee et al. [9,10] studied the effect of elemental boron addition (2 wt%) on the microstructural characteristics of Ti6Al4V-TiB composites fabricated via laser engineered net-shaping process. They reported dispersion of TiB precipitates within the α + β-Ti matrix. In a recent study, Bermingham et al. [11] reported that the trace additions of boron resulted in improved homogeneity of microstructures in additively-manufactured Ti6Al4V. Another study by Attar et al. [12] reported an increase in compressive strength of the Ti-TiB

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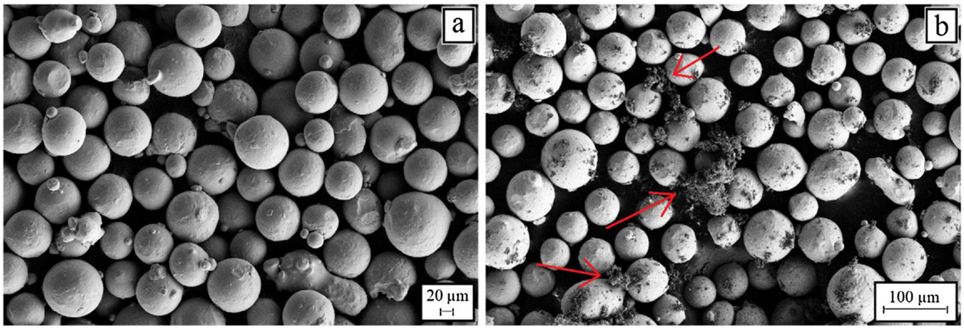

Fig. 1. Powder morphology of (a) Ti6Al4V and (b) Ti6Al4V + B particles. (Note: The boron powder particles are sprinkled over the Ti6Al4V powders for SEM characterisation and are shown by the arrows in (b)).

Table 1
Average chemical composition (wt%) of as-deposited titanium clads, determined by ICP-AES and Leco Combustion.

Sample	Ti	N	O	Al	V	B
Ti6Al4V	Bal	< 0.005	0.17	6.20	4.21	< 0.01
Ti6Al4V0.04B	Bal	0.05	0.21	6.09	4.13	0.04

composites fabricated using the selective laser melting technique, which was not only attributed to the uniform dispersion of TiB particles within the deposited titanium layers, but also to the refinement of α-Ti grains. On the contrary, these studies were conducted either using a powder bed process or wire-fed deposition technique. Furthermore, limited attention only has been given to powder deposition of Ti6Al4V using trace boron additions (< 0.10 wt%). It has been reported that as-cast titanium alloys containing around 0.05 wt% boron resulted in increased ductility in combination with improved strength [13,14].

In this work, blown powder laser deposition process is used. It is proposed that the boron may be effective in refining the microstructure during cladding whilst the formation of TiB will improve the hardness of the clad layer. The objective of this work is to investigate the changes in microstructure and hardness of surface Ti6Al4V clad layers modified with trace boron using the DLD technique.

2. Materials and methods

Pre-alloyed, gas-atomized Ti6Al4V powder (particle size 45–106 µm) provided by TLS Technik and an amorphous elemental boron powder with an average particle size of 1 µm provided by Strem Chemicals were used in this study. In boron containing alloys, the selected intended trace level was 0.05 wt%. Previous studies have reported that this level of boron improves the ductility of Ti6Al4V [13,14]. The morphology of the powder particles is shown in Fig. 1. A wrought titanium grade 5 plate, 16 mm thick, was used as a substrate in this study. The build plate was sand blasted and cleaned with ethanol prior to the deposition trials. The hardness of the titanium build plate was 347 ± 29 HV_2.

The titanium tracks were deposited using a 5 kW Trumpf-POM DMD505 machine. The powder was delivered through a coaxial nozzle having a clearance of 0.71 mm (0.028”). The laser processing was conducted under the protection of argon and helium gas atmosphere to minimise oxygen contamination.

Two single-layered tracks of Ti6Al4V and Ti6Al4V0.04B, each 90 mm in length, were deposited using 1600 W laser power, 60 mm/min traverse speed, and 4.3 g/min powder feed rate. The duration for the deposition was about 90 s. The samples were cut from the midsection of the tracks, and polished using conventional techniques before etching with Kroll’s reagent (2 ml HF, 6 ml HNO_3, and 92 ml H_2O). The average chemical composition of the samples was determined by Spectro ICP-AES as presented in Table 1. The location of this analysis was taken at the midpoint along the clad length. The microstructures were examined under the Olympus BX-61 optical microscope and Gemini SUPRA 40 V P scanning electron microscope. Buehler Vickers hardness tester was used to measure the microhardness of the samples at a load of 300 gf and a dwell time of 12 s.

3. Results and discussion

The macrostructures of the samples are presented in Fig. 2(a–d). The thickness of the deposited layers was about 1.8 ± 0.15 mm. The prior β-Ti grain boundaries are clearly visible in both the bright and dark field images of the Ti6Al4V clad. The microstructure of Ti6Al4V deposit consisted mostly of martensitic α′-Ti needles, with change in orientation of these needles occurring at the grain boundaries as shown in Fig. 2(e). In addition, it was observed that the prior β-Ti grain boundaries and the α-Ti blended together at the clad-substrate (C-S) interface (Fig. 2(f)).

With trace addition of boron, the prior β-Ti grain boundaries were slightly visible only under dark field optical imaging (Fig. 2(d)). The microstructure consisted of fine α-Ti laths dispersed throughout the clad region as shown in Fig. 2(g). This is in accordance with the findings of Horiuchi et al. [15] where the formation of α-Ti in Ti24Nb3Al titanium alloy is related to the boron’s tendency to reduce the martensitic transformation temperature. Moreover, the prior β-Ti grain boundary observed in this deposit was discontinuous, as has been reported by Bermingham et al. [11]. Furthermore, there is clear distinction in the microstructure at the clad-substrate interface (Fig. 2(h)), whereby the clad consists of the fine α-Ti laths and the substrate region consists of coarse α + β-Ti grains.

The variation in the microhardness across the clad for both Ti6Al4V and Ti6Al4V0.04B is presented in Fig. 3. It can be observed that the hardness of the Ti6Al4V clad ranges between 390–450 HV, whereas for Ti6Al4V0.04B, it is 510–600 HV. Moreover, the hardness in the HAZ (heat-affected zone) region is about 350–375 HV for both samples, which is slightly more than the average hardness of the substrate (325 HV). For the Ti6Al4V deposit, the hardness gradually decreases along its thickness until the clad-substrate interface. However, there is a steep decrease in the hardness at the interface between the Ti6Al4V0.04B deposit and the HAZ. It is possible that the presence of oxygen in both the deposited clads can be accounted for an increase in