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Full Length Article

Additive manufacturing of a novel Ti-Al-V-Fe alloy using selective laser melting

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ABSTRACT

Ti-1Al-8V-5Fe (Ti-185) and other Fe containing β -Ti alloys are attractive because of their high strength and low cost. These alloys, however, cannot be produced through ingot casting due to strong Fe segregation and the formation of β flecks. Selective Laser Melting (SLM) was successfully used to produce Ti-185 components starting from elemental Ti and Fe powders, and an Al-V master alloy powder with irregular shape. Microstructure analysis of the as-built components demonstrated that SLM can be used to produce a very fine grain microstructure with nano-scale precipitates and non-detrimental Fe segregation. The findings are interpreted in terms of the rapid solidification conditions during SLM. Compression test results reveal that ultra-high strength and reasonable ductility can be achieved in the as-built as well as heat treated samples.

1. Introduction

Additive manufacturing (AM) is an emerging technology for producing near-net-shaped components directly from powders or wires melted by a high-power-density heat source. The main advantage of AM is its ability to directly produce complex geometries with minimal material waste. New material options are required that take advantage of the corresponding rapid solidification rates.

Titanium alloys provide components with high specific strength and high operating temperatures. In recent years, (near) β -Ti alloys have been widely explored owing to their higher strength, and improved combinations of toughness and fatigue resistance as compared to other Ti alloys [1]. These alloys contain high additions of β stabilizing elements (Mo, V, Cr, Fe). Wide-scale adoption of β -Ti alloys is limited due to high costs, which are partly due to the cost of the Mo, V, and Cr alloying elements. Ti-1Al-8V-5Fe (Ti-185) is a unique low-cost β -Ti alloy, containing lower cost alloying elements, notably Fe, as compared to Ti-10V-2Fe-3Al (Ti-1023) and Ti-5Al-5V-5Mo-3Cr (Ti-5553) while offering high strength and fatigue life. Although Ti-185 was patented more than 50 years ago, it is not commercially viable using traditional processing. This is because strong micro-segregation of Fe occurs during casting [2,3], resulting in large variations in composition and leading to the precipitation of brittle phases. For the few niche applications where Ti-185 is currently utilized, the alloy is heat-treated to produce a microstructure consisting of a β matrix with primary α phases at the grain boundaries as well as a nano-scale distribution of α precipitates within the grain interiors.

Recently, Joshi et al. [4] developed a processing route for Ti-185 consisting of powder metallurgy followed by thermo-mechanical processing. In this way, both the segregation of Fe and the formation of detrimental β fleck phase were bypassed (β flecks are β phase regions strongly enriched with β stabilizing elements such as Fe and/or Cr [5]). Although the properties were excellent (1655 MPa tensile strength and 4–6% elongation), a lengthy and costly sintering treatment and multiple rolling steps were required for component fabrication [4]. Starting from the same material, Devaraj et al. [6] then developed a hierarchical nano-structured alloy with very fine primary and secondary α within the β -matrix by using an aging treatment below the β -transus temperature. This microstructure resulted in a unique combination of strength and ductility, surpassing available commercial Ti alloys.

In the present study, the use of Ti-185 as a novel material for Selective Laser Melting (SLM) (a powder-bed based AM technology) is investigated. Compared to the $\alpha + \beta$ grades, very few studies on AM of β titanium alloys have been published [7–12]. This is thought to be due to the limited powder stock available for SLM. The main objective of this work is to develop a printed component of Ti-185 alloy having

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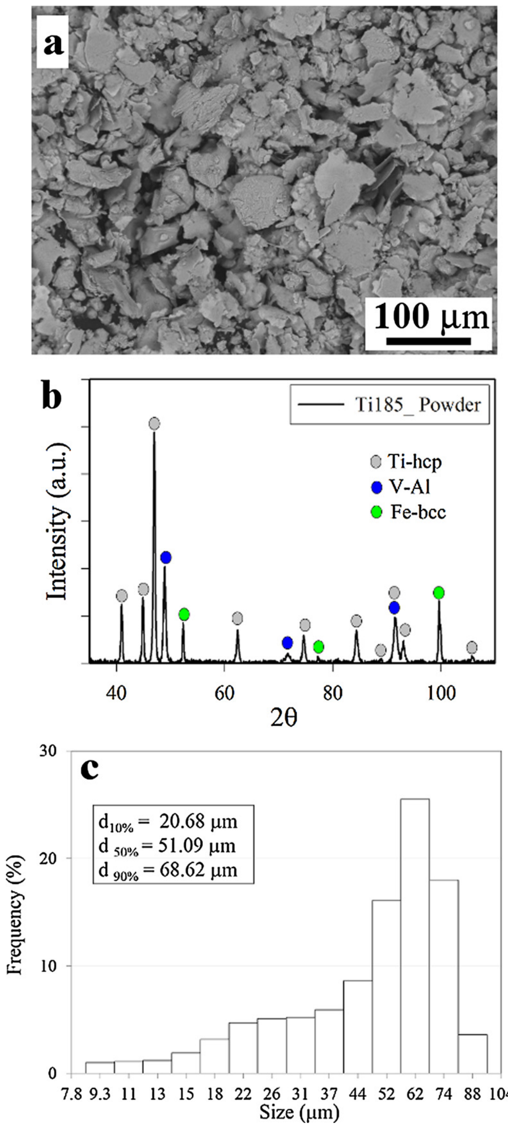

Fig. 1. (a) SEM image of the Ti-185 powder used in this study, (b) XRD pattern of the as-built sample and (c) particle size distribution analysis.

minimal segregation and porosity, and reasonable mechanical properties. During AM of metals, the cooling rates are estimated to reach up to 10^3–10^4 °C/s [13], which could greatly reduce Fe segregation and minimize the formation of the β flecks, ensuring that the optimal component yield strength and toughness is achieved. Eylon and Froes pointed out that Ti-185 should only be used with processes enabling rapid transformation from the liquid to the solid state [14]. It would thus appear that AM, characterized by high solidification rates, is uniquely suited for processing Ti-185.

2. Materials and methods

Ti-185 powder was obtained from ADMA Advanced Materials Products, Inc., Hudson, Ohio. The powder is an elemental mixture of titanium, iron, and a vanadium-aluminum (V-Al) master alloy. First, the powder was ball milled and sieved to achieve the appropriate size distribution for SLM. Ball milling, traditionally used in powder metallurgy, has also been used in recent years to develop elemental powders suitable for AM processes [15,16]. The use of elemental powder as feedstock also contributes to material saving costs and allows for future flexibility in alloy design. The powder characteristics (size distribution, flowability and apparent density) were measured using a laser diffraction technique and Hall tests following ASTM standards B212 [17] and B213 [18]. Second, an EOS-M280 SLM apparatus was used to build a series of sample coupons for metallographic examination and mechanical testing. The base plate was a Ti-5553 near-β titanium alloy, preheated to 80 °C. A stripe laser pattern was used with the laser power, scanning speed, hatch spacing and layer thickness being 370 W, 1035 mm/s, 0.12 mm and 0.06 mm, respectively. During every new layer, the stripes were rotated counterclockwise by ∼67° as compared to the previous layer. This set of parameters was equivalent to a power density of approximately 50.4 J/mm^3, and was used based

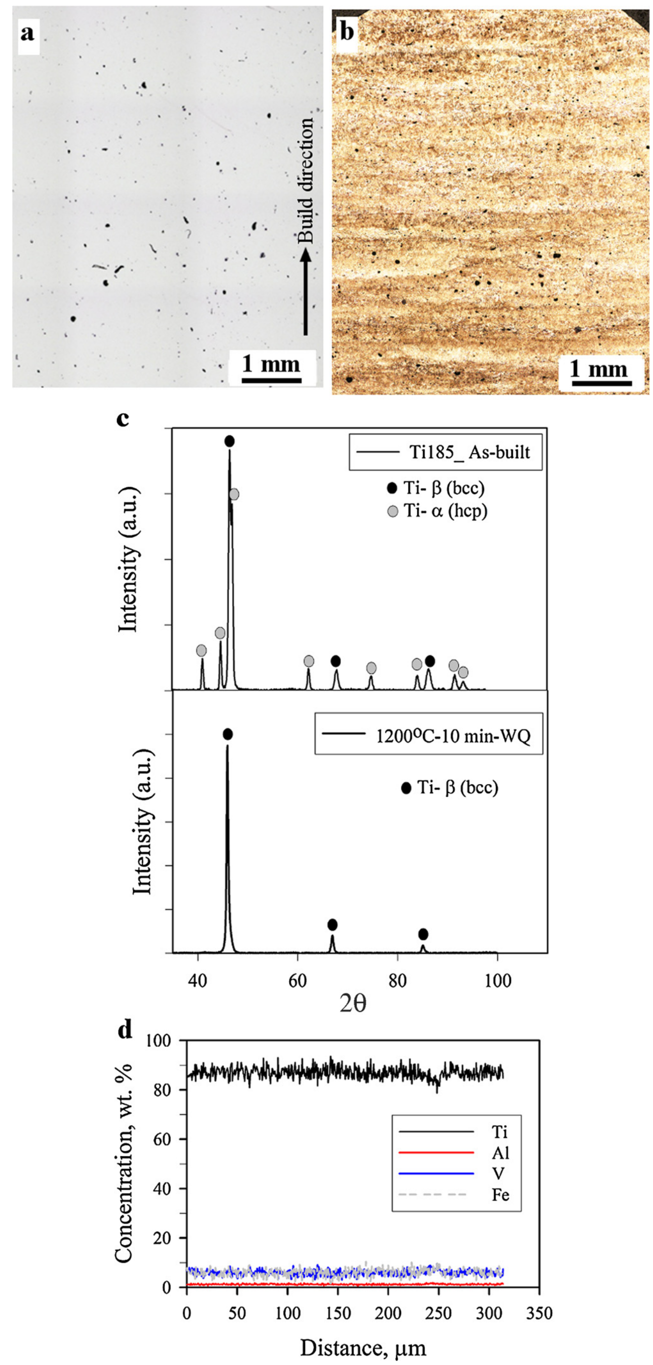

Fig. 2. (a, b) Optical micrographs of the as-built structure in the polished and etched conditions, (c) XRD pattern of the as-built structure and a sample subsequently heated to 1200 °C and then water quenched and (d) EDS line scan in the as-built sample in the build direction. (Note: the Fe and V lines overlap each other).