

Corrosion Studies of an Additive Manufactured Alpha-Beta Ti Alloy

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ABSTRACT

α - β titanium alloys are used extensively in various industries, from aerospace to power generation, oil and gas and bio-medical applications. Production of these alloys, in recent years, has been explored using additive manufacturing methods (AM). The effect of process parameters on the electrochemical behavior of α - β titanium alloys produced by Electron Beam Melting (EBM) was studied. The as-built parts were examined using optical and scanning electron microscopy (SEM) equipped with energy dispersive X-ray spectroscopy (EDS). SEM examination of samples post electrochemical tests was also performed to understand the corrosion mechanisms and relate them to the microstructures and process parameters. The results from this study are presented in this paper.

Key words: Alpha-beta titanium alloys, Electron Beam Melting, corrosion, microstructure, AM, Additive Manufacturing.

INTRODUCTION

Additive Manufacturing (AM), is a manufacturing process whereby an object designed using computer aided design (CAD) is produced by joining layer by layer¹. AM has been used extensively because of the design flexibility it offers compared to conventional manufacturing processes. Several AM

machines are currently available on the market and these can be classified in several ways. For example, it can be based on the material feed stock, energy source, build volume, etc. For metal AM there are mainly two types of power sources, namely, an electron beam or a laser beam. More details on the different AM machines are described in other publications¹.

The AM process is such that a new layer is built on top of the previous layer. This causes repeated heating and cooling of various layers of the built part resulting in a complex microstructure¹. Further, the process parameters used on the AM machine to build the part will also influence the final microstructure.

α - β titanium alloys such as Ti-6Al-4V (UNS⁽¹⁾ R56400), are used extensively in various industries ranging from aerospace to power generation, oil and gas and bio-medical applications. Parts using the Ti-6Al-4V alloy are also produced extensively using different metal AM methods. These parts were reported to have mechanical properties that are superior to conventionally produced alloys, however, depending on the process and parameters used, the corrosion behaviour appears to differ. For parts produced using Selective Laser Melting (SLM) the corrosion performance of the as-built part was inferior to wrought Ti-6Al-4V, while subsequent heat treatment of the AM part improved the corrosion resistance²⁻⁴. It is also reported that the corrosion performance is dependent on the build plane from where the sample was taken. Samples of AM Ti-6Al-4V taken from the XY plane showed better corrosion performance than samples taken from the XZ plane⁵. The inferior performance of SLM as-built parts was attributed to the very low amount of β phase in the part^{4,5}. For parts produced using Electron Beam Melting (EBM) the corrosion performance was found to be comparable with wrought alloys and does not appear to be affected by the porosity in the sample⁶. The improved performance is attributed to the ultrafine grained lamellar α/β phases and a large proportion of β phase in the sample⁷. It shows from the literature that AM parts produced by EBM has corrosion resistance comparable to wrought alloys, but there are only a few studies on EBM built Ti-6Al-4V. Further, the available literature does not discuss the effect of process parameters on the corrosion performance.

In this work Ti-6Al-4V (UNS R56400) alloy was produced using Electron Beam Melting (EBM) with different process parameters. Here, we present the effect of the beam scan speed (represented by the speed function) on the polarisation resistance in 3.5 weight % NaCl solution. The microstructures of the samples before and after corrosion testing were examined using a scanning electron microscope (SEM) equipped with energy dispersive X-ray spectroscopy (EDS) to provide some insights into the effect of this AM parameter on corrosion behavior of Ti-6Al-4V (UNS R56400).

EXPERIMENTAL PROCEDURE

Sample Preparation by EBM

Ti-6Al-4V (UNS R56400) powder used in this study was sourced from AP&C, Canada a GE Additive company. The composition of the powder, in weight percent, from the manufacturer's test certificate is shown in Table 1. For comparison, the composition specified for UNS R56400 is also shown. The particle size distribution was in the range 45 μm to 106 μm .

Square blocks, 40 mm by 40 mm in dimension with a thickness of 8 mm, were fabricated using an Arcam A1 Electron Beam Melting machine⁽²⁾. The samples were built with a powder bed preheat of 730°C. The energy source, i.e. the electron beam, for melting the metallic powder is generated in vacuum by a 3.5 kW tungsten filament thermionic electron gun accelerated to 60 kV. There are five main parameters that control the EBM process, and in turn, the microstructures and properties of the

⁽¹⁾ Unified Numbering System for Metals and Alloys (UNS). UNS numbers are listed in Metals & Alloys in the Unified Numbering System, 10th ed. (Warrendale, PA: SAE International and West Conshohocken, PA: ASTM International, 2004).

⁽²⁾ Arcam EBM, a GE Additive company, Designvägen 2, SE-435 33 Mölnlycke, Sweden.

built parts: maximum beam current; focus offset, speed function, line offset and the powder layer thickness. The first three parameters control the beam power, the beam focus and the scan velocity, respectively. The speed function, a number, is a proprietary function that determines the scan speed and the beam current, for a given material, to achieve a correct melt pool size. At a given build height, increasing the speed function increases the scan speed but the beam current is unaffected. More details on the speed function are available in published literature⁸. In this study we prepared samples using three different speed functions, while keeping all the other parameters constant, as shown in Table 2. In all cases, highly dense samples with relative densities in the range 99.4-99.8% of the theoretical density (TD) of Ti-6Al-4V, were produced, as shown in Table 2.

Table 1. Chemical composition (in weight %) of the alloy examined in this study

Alloy	Aluminium	Vanadium	Iron	Oxygen	Titanium
UNS R56400 Ti-6Al-4V	5.5-6.75 6.36	3.5-4.5 4.06	0.3 (max) 0.21	0.2 (max) 0.13	Balance Balance

Table 2. Electron Beam Melting parameters used for sample preparation

Sample ID	Maximum Current (mA)	Focus Offset (mA)	Speed Function	Approximate Scan Velocity (mm/s)	Line Offset (mm)	Powder Layer Thickness (μm)	Density (% TD)
A	21	5	75	3086	0.1	50	99.7
B	21	5	98	4101	0.1	50	99.8
C	21	5	120	5007	0.1	50	99.4

Microstructural Characterization and Corrosion Testing

Samples for corrosion testing with dimensions approximately $10 \times 8 \times 10 \text{ mm}^3$, were extracted from the as-built blocks as shown in Figure 1(a) such that an area approximately 10 mm by 10 mm in the X-Z plane (parallel to the build direction) was available for testing. A conducting brass screw was attached to the face opposite to that designated for testing using a conducting epoxy mix. The samples were then mounted in epoxy, surface ground using SiC papers from 180 to 2000 mesh size followed by polishing using a solution containing, by volume, 96% colloidal silica suspension, 2% ammonia solution and 2% hydrogen peroxide.

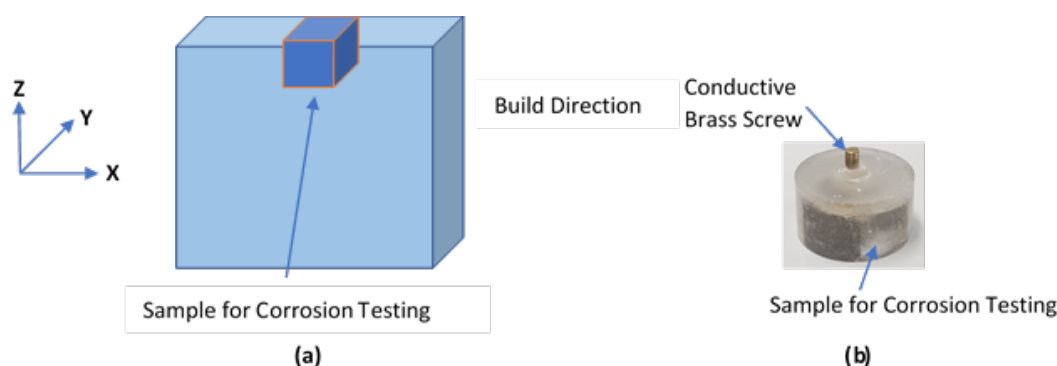


Figure 1: (a) Extraction of samples in the X-Z plane for corrosion testing; (b) samples mounted in epoxy with a conductive brass screw attached.

The as-polished samples were examined using a Field Emission Gun-Scanning Electron Microscope (FE-SEM) equipped with an Energy Dispersive X-ray spectroscopy (EDS) detector to characterize the as-built microstructure.

Open circuit potential and potentiodynamic polarisation measurements were performed using a potentiostat equipped with operating software on the as-built, polished samples. The three-electrode electrochemical cell consisted of the sample to be tested as the working electrode, a graphite counter electrode and a saturated calomel electrode as reference electrode. The tests were conducted in a 3.5 weight % NaCl solution, with a pH 6.6, prepared using analytical grade NaCl and de-ionized water. The solution was exposed to air but was not additionally aerated. The open circuit potential measurement was performed for 18 hours. The potentiodynamic polarisation test was performed at a scan rate of 0.167 mV/s from a potential of -0.4 V to 2 V with respect to the open circuit potential. The corroded samples were examined using the SEM to understand the corrosion mechanisms.

RESULTS

Microstructural Characterization of As-built Samples

The as-built X-Z plane microstructures of Samples A, B and C, built with speed functions 75, 98 and 120, respectively, at a region about 100 μm from the top surface of the build, are presented in the back scattered electron (BSE) SEM images in Figures 2(a)-(c). The microstructure is made up of columnar prior β grains. The columnar nature of prior β grains is a direct consequence of the thermal gradient that exists in the build direction⁹. Within these prior β grains, a transformed $\alpha+\beta$ microstructure with both colony and Widmanstätten morphology is observed. It is evident that the microstructure of Sample C, built with the highest speed function, is significantly finer. This is consistent with the fact that faster scanning speeds result in faster cooling rates for the melt pool, resulting in a finer microstructure^{10,11}. However, as seen from Figure 2(d), the cooling rate experienced by Sample C is still slow enough to prevent the formation of an α' martensitic structure, with fine β phase observed at the α lath boundaries. Note that the β phase shows a brighter contrast in these BSE SEM images due to the presence of V and possibly also Fe, which are β stabilizers in titanium.

Figures 3(a), 3(c) and 3(e) present low magnification BSE images of the X-Z plane microstructures of Samples A, B and C, at a region approximately 3 mm from the top surface of the build; the corresponding high magnification images are shown in Figures 3(b), 3(d) and 3(f), respectively. It is evident from these micrographs that away from the top most region, the microstructures of the samples built with speed functions 75 and 98 display a similar degree of refinement, while the sample built with the higher speed function of 120 is still slightly finer. The low magnification images in these micrographs again show the classic columnar microstructure of additively manufactured Ti-6Al-4V. Comparison of Figures 2 and 3 shows that the faster scanning speed associated with the higher speed function of 120 again results in a slightly finer microstructure compared to the other two samples fabricated with slower speed functions but now the difference is less obvious when compared with the corresponding images from a region close to the top surface, shown in Figures 2(a)-(c). Comparing Figure 3(e) with Figure 2(c) reveals that at this region well away from the top most build layers, the microstructure of Sample C has coarsened. The layer by layer fabrication of the AM processes means that the application of each successive layer significantly influences the thermal profile of the preceding layers by exposing them to repeated thermal cycles¹². In addition, these sample were built with a powder bed preheat of 730°C, which means that the regions away from the topmost layers experience this temperature for a longer time. Both these factors lead to a coarsening of the microstructure away from the top most regions of the build in the X-Z plane. It is well known that heat treatment at temperatures below the β transus (999 $\pm$ 14 °C from¹³) results in decomposition of α' martensite (if