03.31.2020

BERKELEY PUBLICATION

AND RESEARCH INTERNATIONAL

Journal of Pure and Applied Science Vol. 12 No. 9

A REVIEW OF THERMAL BEHAVIOUR AND PROCESSING-MICROSTRUCTURE-PROPERTY OF Ti – 6Al – 4V ALLOYS FABIRICATED BY TWO ADDITIVELY MANUFACTURED TECHNIQUES

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ABSTRACT

This study provides a review of two metal additive manufacturing processes, selective laser melting (SLM) and electron beam melting (EBM) and some common physical phenomena associated with these additive manufacturing (AM) techniques. It then focuses on the following areas: (a) thermal behaviour of Ti6Al4V parts (b) microstructure process property. The porosity in AM Ti6Al4V components and the influence of this defects on mechanical performances are also discussed. The review is not meant to put a ceiling on the capabilities of SLM and EBM processes but to enable readers have an overview on the material properties achieved by these techniques.

Introduction:

Selective laser melting (SLM) and electron beam melting (EBM) are two based additive manufacturing processes used to fabricate metallic parts. Compare to convectional manufacturing methods, the SLM and EBM processes are of great interest due to their numerous benefits. These benefits include freedom of fabricating intricate shapes, optimisation of material usage, eradication of expensive tooling etc. are among the notable benefits of additive manufacturing. The Ti -6Al-4V is recognised as the most popular titanium alloy because it occupies

Keywords: Ti6Al4V, Electron beam melting, Selective laser melting, Microstructure, Porosity

nearly a half of the market share of products in use globally today. The alloy was originally developed for aircraft structures in the 50s. The Ti -6Al-4V is predominant and dominates the aerospace industry and also found its applicability in automobile, energy, chemical as well as biomedical industries (Boyer, 1996). The characteristics of Ti -6Al-4V of having low density, high strength, high corrosion resistance and biocompatibility make it attractive for such application as bridges, marine and implants due to its high corrosion resistance to most corrosive acids and alkalis (Cui, et.al, 2011 and Emmelmann, et, al., 2011).

Compared to traditional manufacturing techniques, the most important advantage of AM is its freeform fabrication capability of intricate pars directly from feedstock materials by eliminating manufacturing methods such as extrusion, forging, casting and machining processes in order to achieve desired shapes. Similarly, the near net shaping capability enables AM to be cost- effective technique thereby minimise waste.

Additive manufacturing (AM) processes comprise a large range of versatile techniques. AM techniques such as SLM, EBM and direct energy deposition (DED) are mostly used when fabrication of dense metallic structures and powder-based are to be put into consideration (Herzog et.al., 2016). The processes involved interaction of laser or electron beam with feedstock powders and a molten pool is produced where both rapid melting and re-solidification takes place. As a result of the highly localised heat input and short interaction time, there is large temperature gradients and high cooling rate (Shin et.al., 2018). However, high cooling rates result in non-equilibrium microstructures which could require heat treatment for certain applications. Murr et al. (2009) observed that elevated temperatures help minimise thermally induced residual stresses and the formation of non-equilibrium microstructures. These distinctive thermal features vividly affect as-built microstructures and lead to high residual stresses in built Ti -6Al-4V products which is a function of their macroscopic performances. Initially, the powder would be preheated at a very high scan speed, large focal spot and low beam current by the high intensity electron beam. The process of the preheating could help lower moisture content and consequently reduce the possibility of oxygen pickup. Preheating may reduce the residual stress buildup by bringing down the temperature- gradient between successful layers during processing. The electron beam scans the powder after the melting stage at a lower scan peed with higher beam current. The part is then allowed to cool slowly from 700^0C to room temperature.

Furthermore, the defects inevitably formed during AM processes would considerably deteriorate the mechanical and fatigue properties of the products (Beretta and Romano, 2017). Therefore, SLM and EBM built component may require supporting structures to avoid bending or distortion during manufacturing.

Earlier studies carried out by different researchers revealed characteristic microstructures and related properties for SLM and EBM produced material. In the study of Thijs et al. (2010), there was influence of process parameters and the scanning strategy on the microstructural evolution during SLM processing of Ti -6Al-4V materials. It was observed that the ensuing microstructure revealed acicular martensite as a consequence of a very high cooling rates. The microstructure was considerably affected by factors like high localised heat inputs, short interaction times local heat transfers and processing conditions. In the finding of Facchini et al. (2009), SLM produced Ti -6Al-4V microstructures is completely martensitic. The effect of process parameters in terms of microstructure, densification, surface roughness and microhardness of Ti -6Al-4V was studied by Song et al. (2012) with a suggestion that a laser power of 110W and scan speed of 0.4m/s could be obtained in a continuous melting mode at maximum density.

Microstructural characterisation carried out by Murr et al. (2009) on Ti -6Al-4V produced by EBM revealed acicular α and associated β microstructure. According to Al-Bermani et al. (2010) prior β grains form epitaxially and extend through several layers as a result of the thermal gradient in the build direction.

The microstructural features of SLM and EBM produced samples have been studied, few attention has been paid to thermal behavior and processing microstructure- property- relationship of these processes. Consequently, the objectives of the present paper are to evaluate the thermal behaviour, processing- microstructure- property relationship for the additively manufactured Ti -6Al-4V using SLM and EBM techniques. Also, an interesting point of this work involved evaluating the porosity in the two processes reviewed. The knowledge included in this study can serve as a guidance to address the shortcomings of AM processes and contribute to the development of applications in the practical production processes for Ti -6Al-4V alloy.

Thermal Behavior of Ti6Al4V

AM processes are renowned by remarkable differences in both input energy and thermal behavior. Liu and Shin (2018) explained that the processes involve complex multi-physics and non-equilibrium phenomena that usually affect power, scan speed, scan strategy, layer height, etc. of a group of processing parameters. Interaction between a laser/electron beam and precursor powders similarly depend on powders absorptivity, physical properties and particles sizes. The approximate input energy density E (in J/m^3) is used so as to provide a basic starting point for evaluating differences in AM processes. However, the absorbed energy density is express as:

$$E = \frac{\alpha P}{V.h.t}$$

Where P is the power (J/s),

V is the scan speed (m/s)

h is the hatch spacing (m)

t is the layer thickness (m) and α is the absorptivity.

SLM process typically depends on conduction through the unmelted powders surrounding the component to be produced in order to dissipate heat and similarly, the parts fabricated using EBM technique are usually surrounded by incompletely melted metallic powders and consequently conduction governs the heat transfer in the EBM process (Liu and Shin, 2018). Also, heat loss by radiation plays a role which could be neglected compared to conduction.

Owing to the highly concentrated energy source couple with a very short interaction time, the molten pool would produce a high temperature and cooling rate. As reported by Yadroitsev, Krakhmalev and Yadroitsava (2014), a maximum temperature of around 2710K was observed in the Ti6Al4V molten pool produced by SLM. For example, Cheng et al. (2014) found that the molten pool temperature was approximated to be between 1900^0C and 2700^0C for the EBM produced part whereas, Price et al. (2013) carried out a specific study using thermograph and obtained a molten temperature of 2500^0C. Likewise, Antonysamy, Meyer, and Prangnell, (2013) recorded a cooling rate of 10^4K/s by simulation. The cooling rate in EBM produced Ti6Al4V part had the same scale with SLM. However, the thermal behavior of EBM fabricated parts is different because it has a range of 600 – 750^0C build temperature (Weiwei et al., 2011). The high build temperature of EBM behaves like a post heat treatment process and the fabricated parts consequently present different microstructure and materials properties.

Microstructure of Ti6Al4V

Primarily, the microstructural evolution is a function of cooling rate. For example, materials processed with SLM and EBM undergo a very high cooling rates. Similarly, microstructure directly governs the material properties of final products in accordance with the manufacturing processes used. The microstructure of SLM and EBM produced Ti6Al4V are comparatively reviewed in this section.

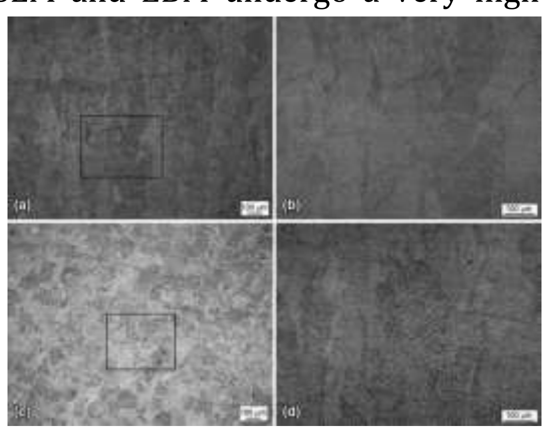

Fig. 1 Optical micrographs of SLM produced samples. (a) Longitudinal cross-section showing columnar grains. (b) High magnification longitudinal showing fine ʹα martensitic laths. (c) Transverse cross-section showing bundles columnar grains. (d) High magnification transverse showing fine ʹα martensitic (Rafi et al., 2013).

Figure 1 shows the optical microstructure of SLM processed Ti6Al4V revealing a complete martensitic ʹα microstructure (Thijs et al.,2010). The origin of martensitic laths is from the prior β grains boundaries that fill the columnar grains. Martensitic lath can be observed as revealed in the SEM-SE image in Fig. 2. The width of the lath is about 1-2 mμ and its length is close to the width of the columnar grains.

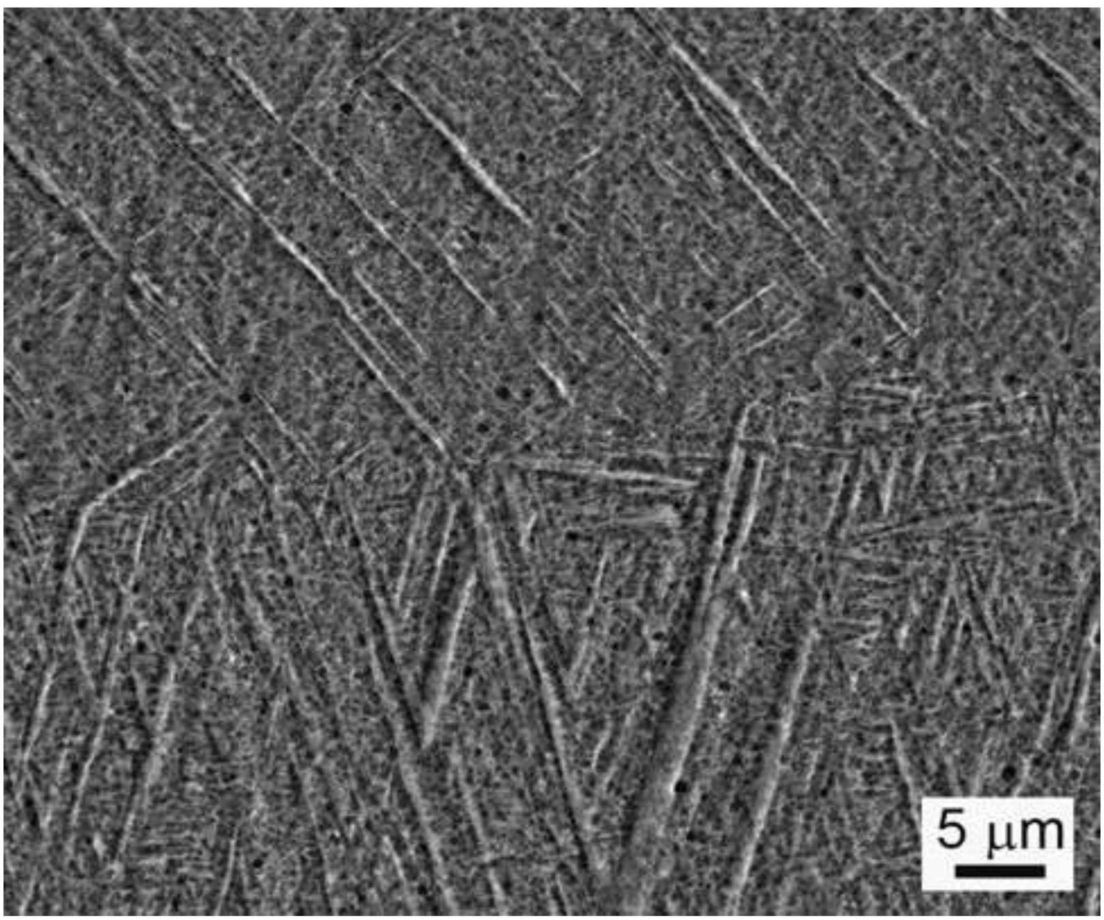

Fig. 2 SEM-SE image of SLM- produced Ti6Al4V

The optical micrographs of EBM-produced Ti6Al4V is presented in Fig. 3 showing a completely different microstructure and mainly composed an α phase and a small amount of β within prior β columnar grains. The α phase possessed a lamellar morphology and the β surrounding the lamellar boundary. Consequently, the SLM and EBM processes produce different microstructures for Ti6Al4V. In both processes, prior β columnar grain boundaries are obviously visible. This indicates that the primary mode of solidification in both cases remains β, which is one of characteristic of Ti6Al4V alloys regardless of the process used. Hence, the difference in microstructure is as a result of the differences in cooling rate during transformation of β to α as it cools through the transus temperature. Subsequently, there would be a corresponding difference in mechanical properties between SLM-produced and EBM-produced samples.

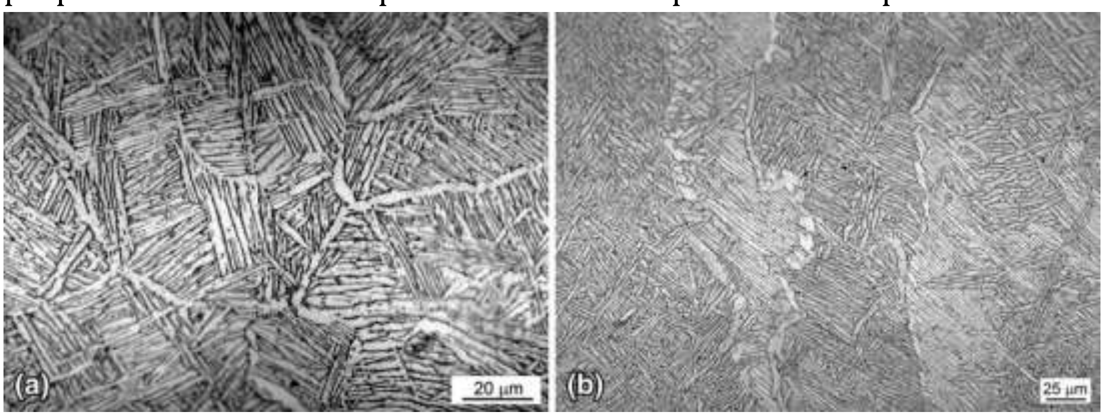

Fig. 3 Optical micrograph of EBM- produced Ti6Al4V samples (a) Transverse cross- section and (b) Longitudinal cross- section

Process Property of Ti6Al4V

A study revealed that the mechanical and thermal behaviors of the SLM Ti6Al4V fabricated parts are considerably affected by both the internal voids and the residual stress in the components produced. For example, Leuders et al. (2013) discovered that the tensile strength and fatigue are strongly affected by the pores size and the study of Simonelli (2014) also demonstrated that the microstructure of the SLM Ti6Al4V parts alters the mechanical properties of these parts. According to Kasperovich et al.

(2016), the SLM process parameters showed a strong influence on the surface quality, voids characteristics, microstructure and mechanical properties of Ti6Al4V parts. Similarly, Zhai, Galarraga and Lados (2015) achieved the same results using EBM technique. In the production of Ti6Al4V using EBM technology, a function is established to control the beam speed and energy during fabrication process so as to enhance the thermal property of the components produced (Price et al., 2014).

Porosity in Ti6Al4V

Theoretically, AM techniques could produce a completely dense structure, however non optimal deposition parameters would result in porosity of the parts. Uncontrolled porosity is really very common in AM fabricated parts. For example, an uncontrolled pore in Ti6Al4V parts will deteriorate the material properties. Using the X-ray tomography, Leuders et al. (2013) identified a porosity of 0.23% in SLM specimens. Ackelid and Svensson (2009), characterised the porosity in EBM parts and found a porosity of 0.17%.

In order to decrease the pores, the as- built AM parts are usually subjected to post-processing heat treatment to reduce the pores. Kasperovich and Hausmann (2015) found that only hot isostatic pressure (HIP) have a significant positive effect to reduce porosity in Ti6Al4V parts; as the pore volume fraction reduced from 0.08% to 0.01% after HIP leading to reduced pores size.

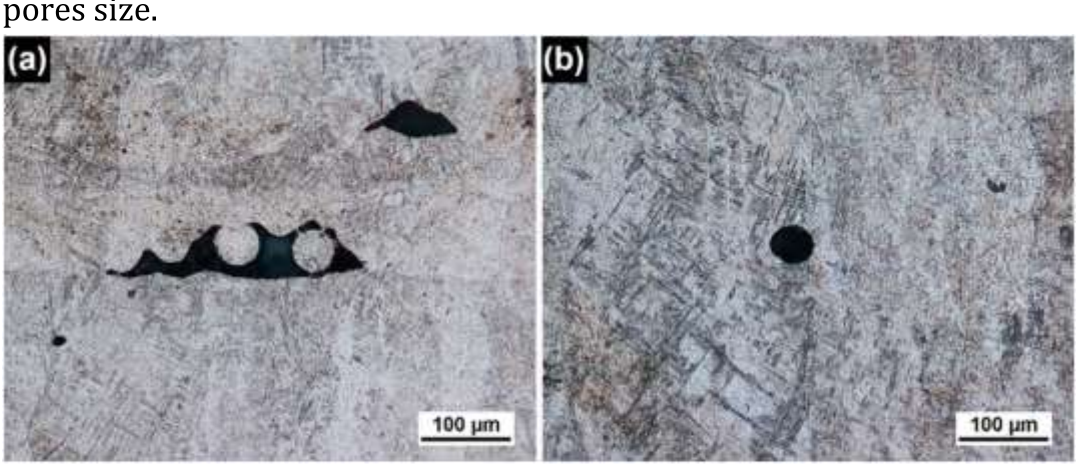

Fig. 4 Porosity in EBM of Ti6Al4V part: (a) lack of fusion and (b) gas pore (Galarraga et al., 2016)

Regardless of the process route taking, AM processes have inherent limitations such as risk of porosity, high affinity to oxygen, presence of surface roughness and residual stresses. The shortcomings impose a severe detrimental effect on the mechanical performances of as-built part.

Conclusions

In this paper, thermal behavior and microstructure-process properties of SLM and EBM built Ti6Al4V components were comparatively studied. The following conclusions were drawn

1. The SLM and EBM thermal behaviors processes reveal an acicular α martensitic microstructure but high build temperature involved in the EBM process results to an α + β lamellar microstructure.
2. The microstructure of SLM produced parts were composed of an α' martensitic phase, whereas the EBM processed parts contain mainly α and a small amount of β phase. The differences are related to the cooling rates experienced as a result of the processing conditions associated with SLM and EBM methods.
3. The main difference between the processes boils down to the cooling rate, however the same material processed using SLM and EBM could have different properties. The property requirements for a part produced for biomedical applications could differ from a part produced meant for aerospace applications.
4. The porosity and surface roughness in AM Ti6Al4V aid crack initiation. Post machining and heat treatments could considerably weaken the crack initiation and increase the fatigue life of Ti6Al4V fabricated by AM technologies.

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ISSN: 1399-8466