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A Review of Powder Bed Fusion for Additively Manufactured Ti-6wt.%Al-4wt.%V

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Abstract

Selective Laser Melting (SLM) a form Powder Bed Fusion (PBF), is a type of Additive Manufacturing (AM) process which has the ability to manufacture complex geometric parts that cannot be produced by traditional means. Ti_6AL_4V is an α + β titanium alloy and is commonly used within the medical and aerospace industries. It is one of the few technical metal alloys that can be processed by PBF. This contribution will review the issues related to microstructure formation, residual stress, and porosity formation that can arise within Ti_6Al_4V parts produced by the PBF process. In particular, the influence of the manufacturing process parameters and the presence of defects on the mechanical properties will be reviewed. High thermal gradients and rapid solidification of the molten powder can lead to the development of a martensitic microstructure and other specific defects within the as-built part. Defects have a negative impact upon mechanical properties. Porosity, balling, lack of fusion and delamination are common examples of process-specific defects. The requirement for secondary processing of the additively manufactured components to improve mechanical properties will be reviewed with a particular focus on the requirement for the Hot Isostatic Pressing (HIP) processing.

Keywords: Additive Manufacturing, Selective Laser Melting, Ti_6Al_4V, Defects, Hot Isostatic Pressing

1. INTRODUCTION

SLM a form of PBF, is one of seven types of AM processes identified according to (ISO/ASTM 52900:2015, Additive Manufacturing). Defining AM by a process of joining materials to make parts from 3D model data, usually layer on layer. Hence allowing parts with a high complex structure to be manufactured, otherwise unachievable by traditional methods. According to BS ISO/ASTM 52910-17, the PBF process uses an energy source to melt the powder particles to form part cross-sections. The deposited powder upon the preheated platform, forms a melt pool upon exposure with the high temperature laser. The rate at which the melt pool solidifies, determines the formation of the microstructure. The present phases, grain morphology and the distribution of the microstructure defines the part properties. Ti_6Al_4V is an α + β metal alloy where the 6wt%. aluminium stabilises the α phase and the 4wt%. vanadium stabilises the β phase. Approximately 60% of employed titanium alloys produced are Ti_6Al_4V. The Ti_6Al_4V alloy is commonly used in aerospace and medical industries due to its high specific strength, good fatigue resistance and biocompatibility properties.

2. DEFECTS

Despite the process specific benefits, numerous as-built characteristics require resolving to acquire an acceptable part for application. Porosity, martensitic microstructure and residual stress are examples of commonly found defects which arise via the SLM process, negatively impacting the part properties. Rapid solidification of the molten Ti_6Al_4V powder, promotes formation of acicular martensite. Associating high tensile strength and poor ductility part properties. Leuders et al. (Leuders *et al.*, 2013) showed that pores have a significant impact on fatigue behaviour, initiating crack growth. Pore generation is a result of powder contamination, evaporation or local voids after deposition of the layers. High thermal gradients and rapid solidification within the SLM process, encourages the development of residual stress. Having a strong impact upon crack initiation and growth, promoting failure. Reduction or elimination of defects from SLM parts can be achieved via process optimisation or post-processing. For this to transpire, the relationship between the processing parameters, microstructure and mechanical properties is critical in developing an application-specific part.

2.1 MICROSTRUCTURE

Cyclic heat treatments exist throughout the build of SLM components. Consequently, the microstructure is always stressed, orientated and segregated from rapid solidification, directional cooling and complex thermal history. The cooling rate of the melt pool is dictated by the surrounding ambient temperature or the build platform temperature, within the SLM process. Shunmugavel and Polishetty (Shunmugavel and Polishetty, 2015) compared the microstructure and mechanical properties of wrought and SLM Ti_6Al_4V cylindrical rods. In the longitudinal direction, the wrought bar consisted of full equiaxed microstructure with inter granular β. The microstructure within the as-built SLM Ti_6Al_4V rods was inhomogeneous and consisted of fine acicular α'grains within the β grain boundaries. Consequently, the ultimate tensile strength and yield strength within the SLM rods was higher in comparison with the wrought rods in the transverse direction, as shown in *figure 1*. The percentage of elongation in the as-built SLM rods ranged from 1-7%, compared with the wrought rods ranging from 19-21%.

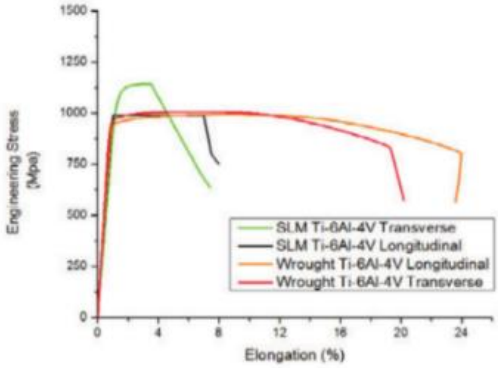

Figure 1- Stress-strain curve for the wrought and SLM Ti-6Al-4V (Shunmugavel and Polishetty, 2015)

2.2 POROSITY

Large thermal stresses and a melt pool instability can generate defects within the as-built part. Porosity, balling effect, lack of fusion and delamination are examples of the typically found defects within SLM Ti_6Al_4V components. Porosity in Ti_6Al_4V has a direct impact upon mechanical properties, in particular fatigue strength promoting crack growth initiation. Porosity within the SLM part can be associated with the energy density (J/mm^3), defined as the average energy density per unit volume of material. Zhou et al. (Zhou *et al.*, 2018) showed that the impact the bulk energy density has upon the fine acicular martensite and the lamellar α phase. Bulk energy density below $533 J/mm^3$ was considered to be too low, leading to partial melting of the powder thus forming more equiaxed grains. Kasperovich et al. (Kasperovich *et al.*, 2016) studied the relationship between porosity and the processing parameters of Ti_6Al_4V in SLM. Laser power and laser velocity showed to have the largest impact upon the porosity fractions. A minimum porosity fraction of 0.042 ± 0.008% was achieved by process optimisation.

The SLM process is becoming an established technique for manufacturing porous metal implants due to the controllability over geometrical and mechanical parameters. The success of a porous biomaterial is relative to the selection of the morphological parameters including the average pore size and porosity. Bulk porosity value above 50% and an average pores size ranging from 50 to 800μm is the allowable tolerance for bone growth.

2.3 RESIDUAL STRESS

Large thermal gradients generated with the SLM process leads to a variation in elastic deformation, resulting in high levels of residual stress within the as-built part. Magnitude dependant, this can potentially lead to warping distortion and stress cracking within the SLM component. Ali et al. (Ali *et al.*, 2017) reviewed the effect scan strategy had upon residual stress and mechanical properties within Ti_6Al_4V SLM parts. At a 90° alternating scan strategy, the minimal porosity and residual stress was achieved at 0.1% and 107MPa respectively. Despite, rescanning with a 150% energy density the residual stress reduced by 33%, it had severe permutations upon the mechanical properties causing premature failure. Mugwagwa et al. (Mugwagwa *et al.*, 2018) considered the influence that the laser power, scanning speed and layer thickness in relation to the residual stress distortions. At a laser power of 180W and layer thickness of 30μm, the distortion increased from 0.38mm to 1.18mm as the scan speed increased from 400mm/s to 1000mm/s respectively. Vrancken (Vrancken, 2016) stated reduction of residual stress can be achieved by a high laser power, low scan speed, thicker layers, shorter scan vectors and the use of preheating. Preheating of the build platform to 400°C showed a 50% reduction of residual stress. Further research regarding residual stress is required specifically within parts produced by SLM.

3. POST PROCESSING

Despite the capability to optimise the process parameters to limit defects, a heat treatment application generates a part with properties similar or better to the wrought of the same material. Heat treatments of the Ti_6Al_4V alloy can be categorised into two groups in relation to the heating temperature. Supertransus and Subtransus, whereby the heating temperature is above or below the β transus at 995°C respectively. Zhang et al. (Zhang *et al.*, 2018) reported that all SLM produced Ti_6Al_4V parts when heat treated below the β transus temperature had higher yield strengths and compressive strengths compared with the as-forged counterpart. Heat treatment can transform the microstructure in Ti_6Al_4V parts from acicular martensite to a stable α + β phase, improving mechanical properties.

HIP, a popular heat treatment method for AM parts, utilises high pressures and temperatures to remove the specified defects. Leuders et al. (Leuders *et al.*, 2013) researched the relationship between microstructure, defect and mechanical properties under cyclic loading for SLM processes Ti_6Al_4V parts. The fatigue behaviour was investigated in as-built, heat treated and HIPed Ti_6Al_4V parts. Results showed that the theoretical relative density in five SLM sample parts after HIPing was 100%, as the pore size was reduced below the 22µm detection limit. The average fatigue life for an as-built and heat-treated part ranged from 27,000 to 290,000 cycles to failure. Compared with the HIPed samples were the test was stopped at 2×10^6 cycles, as no sample had undergone failure. Wauthle et al. (Wauthle *et al.*, 2015) explored the effects of build orientation and heat treatments upon the microstructure and mechanical properties of SLM produced Ti_6Al_4V lattice structures. Analysis showed that regardless of the build orientation or unit cell orientation, the three heat treatment conditions examined; as built versus stress relief and HIP, have a clear influence upon mechanical properties. HIP reduced the tensile strength by approximately 15% compared with the as-built part however the strain at fracture increased from 25-70%.

4. Conclusion

Several artefacts relative related to metal additive manufacture or Ti_6Al_4V have been reviewed in this paper. These features include observations of microstructure and unwanted artefacts such as defects (e.g. porosity) and residual stress. An important observation for AM Ti_6Al_4V parts is that to strain to fracture significantly reduced compared to the wrought alloy counterparts. Post processing, particularly HIPing, of the Ti_6Al_4V parts can be utilised to reduce porosity within the as-built part.

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