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Optimising the mechanical properties of Ti-6Al-4V components produced by wire + arc additive manufacturing with post-process heat treatments

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Wire + Arc Additive Manufacturing (WAAM) is a promising manufacturing process for producing large aerospace components. Based on welding technology, the process is highly affordable, has a very high deposition rate and is not limited by chamber size. Ti-6Al-4V is a promising candidate material for this technology given that it is extensively used in aerospace applications and some large, high buy-fly ratio components can be more efficiently produced by WAAM than via the conventional machining from billet approach. There is currently limited knowledge about whether additional post processes including heat treatments and hot isostatic pressing are necessary to unlock the optimal mechanical properties of Ti-6Al-4V components produced by WAAM. This work explores a range of different post process treatments and the effects on the microstructure and tensile properties of Ti-6Al-4V components produced by WAAM. The relatively slow cooling rate (10-20Ks^{-1}) during the β-α transformation produced Widmanstätten-α and offered an optimal balance between strength and ductility. Hot Isostatic Pressing (HIPing) removed gas porosity but was not effective in improving strength or ductility. Residual tensile stresses in as-built components severely impair ductility and should be removed through stress relief treatments.

1. Introduction

Additive Manufacturing (AM) has emerged as a promising manufacturing process for producing bespoke components, particularly from high cost materials. Powder bed AM technologies such as Selective Laser Melting (SLM) are relatively mature and have received significant attention in the production of Ti-6Al-4V components. AM technologies incorporating wire feedstock are beginning to emerge and offer advantages including high deposition rates and the potential for large part sizes. The wire based AM processes share a number of similarities in terms of the size, shape and quality of potential parts but differ in terms of the heat source (electron beam, laser beam, plasma arc, electric arc etc.) and the chamber requirements (vacuum, inert gas or atmosphere exposed) [1,2]. Unlike powder bed AM technologies such as SLM, which are characterised by very small melt pools and very rapid heating and cooling rates approaching 10^3-10^8 Ks^{-1} [3], wire based AM technologies involve melting a very large volume of metal[1] under slower scan speeds and results in considerably higher deposition rates, slower cooling rates and generally coarser microstructures [2]. Of these technologies, Wire + Arc Additive Manufacturing (WAAM) is amongst the most affordable because it based on inexpensive Gas Tungsten Arc Welding technology [4]. Furthermore, despite being an out of chamber process exposed to the atmosphere, it is possible to fabricate high quality titanium parts with minimal oxygen pick-up using low cost localised inert gas shielding [5]. While unlikely to be a net shape AM process (post machining is required to achieve necessary tolerances), wire based AM

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[1] The melt pool diameter can exceed 10 mm during WAAM, compared to SLM which can approach 0.1 mm in diameter.

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technologies such as WAAM have considerable potential in fabricating large-scale ribbed components for aerospace applications as this substantially reduces the machining required if the component was to be otherwise produced from a wrought billet.

A notable difference between wire based AM processes and established powder-bed AM processes is the size of the molten pool, slower torch travel speed and higher material deposition rates which subsequently determine important solidification parameters such as the temperature gradient G, solid growth rate R and the cooling rate (product of G and R). Bontha et al. [6] modelled laser deposition of Ti-6Al-4V (LENS process) and found that commonly used small scale laser deposition parameters (representative of powder bed technologies) will produce temperature gradients well above 10,000 Kcm^{-1} and growth rates of the order of 0.1cms^{-1} resulting in fully columnar microstructures. However, the temperature gradients substantially reduce by more than an order of magnitude (<1000 Kcm^{-1}) when larger scale AM processes were modelled (that tend to be more representative of conditions experienced during WAAM) and it was predicted that equiaxed coarse grained microstructures could form. The scale of the WAAM process means that cooling rates and therefore microstructures and properties will naturally vary from SLM.

It is now widely accepted that the rapid cooling during SLM of Ti-6Al-4V under most processing conditions results in an as-built microstructure containing very fine acicular α or α' with corresponding high strength and moderate to low ductility on account of the small slip length [7]. It is also widely understood that the AM of Ti-6Al-4V produces highly textured columnar grains [8] and this, as well as the incomplete fusion of powder particles during manufacture [9,10], can cause substantial anisotropy [11]. Many researchers have shown that post-build heat treatments and Hot Isostatic Pressing (HIPing) are effective in improving ductility at the expense of some strength of Ti-6Al-4V produced by powder bed AM processes [9,12–14]. HIPing in particular is very effective in improving the fatigue life and ductility especially during certain SLM processes where unmelted powder and porosity remain. Other researchers have shown that the selection of processing parameters for SLM (such as scan rate) has substantial influence on the densification of Ti-6Al-4V and when optimised can result in as-built components with negligible porosity and improved ductility [15,16].

While a detailed understanding of the effect of processing parameters and post process treatments of Ti-6Al-4V produced by popular powder bed AM technologies is beginning to emerge, there is still uncertainty surrounding how these same factors influence the microstructure and mechanical properties of Ti-6Al-4V produced by WAAM. Initial research has shown that WAAM can produce high quality Ti-6Al-4V components with mechanical properties equalling or exceeding other AM processes in the as-built state. For example, the slower cooling rates during WAAM prevents the formation of α' martensite [17] and this greatly improves the ductility of as-built products which is reported to be in the range of 7–10% in the horizontal direction (normal to build direction) and 12–16% in the vertical direction [4,18–20]. In contrast, when using optimised scan parameters that minimise the presence of porosity during SLM or LENS the typical ductility of Ti-6Al-4V is in the range of 11–12% [15,16]. However, when processing parameters are not necessary optimised during SLM the ductility is generally less than 10%. In powder bed AM processes the ductility is known to be extremely sensitive to the presence of lack of fusion defects and porosity but these can be greatly eliminated by post-process HIPing. For example, Kobryn and Semiatin [9] reported ductility as low as 0.8% in stress-relieved Ti-6Al-4V produced by LENS and this poor result was attributed to lack of fusion defects. However, after being subjected to HIP the porosity was closed and ductility greatly improved to almost 12%.

In light of the coarser microstructure produced and differences in the process it remains unclear whether Ti-6Al-4V produced by WAAM necessitates additional post process heat treatment or expensive HIPing processes. Very limited work exists on the effects of heat treatment on the mechanical properties of Ti-6Al-4V produced by WAAM. Brandl and co-workers [20] performed heat treatment at 873 K and reported limited improvement on the mechanical properties compared with the as-built state but at 1116 K the ductility improved considerably at a marginal expense of strength. Bermingham et al. [21] also performed heat treatment at 1323 K on Ti-6Al-4V produced by WAAM and found that it had no influence on the compressive ductility of Ti-6Al-4V but did considerably reduce the compressive strength. To the authors' best knowledge there is no literature available which investigates the effect of HIPing on the microstructure and tensile properties of Ti-6Al-4V produced by WAAM and compares this to the as-built or other heat treated conditions. The fact that WAAM is not as susceptible to the same incomplete fusion defects as SLM or LENS (blown powder) may indicate that expensive HIPing processes are not necessary; although on the other hand the potential for entrapment of gas porosity remains. Furthermore, the cooling rates during WAAM are much lower than typical powder bed processes so the tendency to form α' martensite is reduced. The purpose of this research is to compare the microstructure and mechanical properties of Ti-6Al-4V produced by the WAAM process in the as-built, stress relieved, heat treated and HIPed conditions and identify the post build processing conditions that yield the most optimal tensile performance.

2. Experimental method

The aim of this work is to compare the microstructures and mechanical properties of Ti-6Al-4V components produced by Wire + Arc Additive Manufacturing that are subjected to different post-build treatments. Details about the equipment and base experimental set up for the WAAM process used here are available elsewhere [21]. Ti-6Al-4V wire was used as the feedstock (initial composition: 5.95 wt% aluminium, 4.02 wt% vanadium, 0.07 wt% oxygen) and a wrought Ti-6Al-4V base plate was used as a substrate for the deposits. A trailing shield supplying high purity argon was used to protect the components as they cool which resulted in contamination free surfaces (the components had a shiny, silver surface appearance). Recent research has demonstrated negligible oxygen pick-up from the atmosphere when using the same trailing shield and deposition conditions for Ti-6Al-4V [5]. Each deposit was created by moving the welding torch in a linear direction and feeding wire into the molten pool, which subsequently solidifies to make a layer. A subsequent layer was then deposited over the first by increasing the height of the torch. The temperature at the end of deposition[2] was measured using a non-contact IR pyrometer, calibrated for emissivity against ultra-high purity titanium (99.995% purity). Calibration was performed by melting a stationary pool of the high purity titanium and experimentally determining the emissivity against the measured thermal arrests occurring at known phase transformation temperatures as it cooled (L→S at 1668 °C and $\beta \rightarrow \alpha$ at 882 °C). The average emissivity from three calibration tests was 0.2907 at the solidification temperature and 0.2909 at the $\beta \rightarrow \alpha$ transformation temperature for the high purity

[2] The temperature was measured at the end of the layer after the arc was terminated. It was not possible to measure during deposition as radiation from the arc interfered with the pyrometer, and the trailing shield prevented direct measurement because it enclosed the cooling metal.