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The effectiveness of combining rolling deformation with Wire–Arc Additive Manufacture on β-grain refinement and texture modification in Ti–6Al–4V

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ABSTRACT

In Additive Manufacture (AM), with the widely used titanium alloy Ti–6Al–4V, the solidification conditions typically result in undesirable, coarse-columnar, primary β grain structures. This can result in a strong texture and mechanical anisotropy in AM components. Here, we have investigated the efficacy of a new approach to promote β grain refinement in Wire–Arc Additive Manufacture (WAAM) of large scale parts, which combines a rolling step sequentially with layer deposition. It has been found that when applied in-process, to each added layer, only a surprisingly low level of deformation is required to greatly reduce the β grain size. From EBSD analysis of the rolling strain distribution in each layer and reconstruction of the prior β grain structure, it has been demonstrated that the normally coarse centimetre scale columnar β grain structure could be refined down to <100 μm. Moreover, in the process both the β and α phase textures were substantially weakened to close to random. It is postulated that the deformation step causes new β orientations to develop, through local heterogeneities in the deformation structure, which act as nuclei during the $\alpha \rightarrow \beta$ transformation that occurs as each layer is re-heated by the subsequent deposition pass.

1. Introduction

Near-net-shape fabrication of metallic components by Additive Manufacture (AM) is an important new technological area with many potential applications in the aerospace industry (e.g. [1–17]). AM involves building parts by sequentially consolidating 2D slices of material that are fused together by a focused heat source [1–3]. A range of AM processes are now available, mainly based on laser or electron beam systems, that use powder or wire feedstock [1–12]. Of these techniques, powder bed methods allow more geometrically complex components to be produced, but the part size is restricted by slow build rates and the limited dimensions of the working chamber [1–4].

Recently, a low cost wire-based AM process that exploits standard welding technology has become of interest to industry [9–11]. In Wire–Arc Additive Manufacture (WAAM) a consumable wire is fed at a controlled rate into an adapted electric arc (or plasma) welding torch that is translated by a robot [9–12]. Material is built up in the form of a weld bead that is overlaid on previously deposited tracks. Shielding can be provided by an inert gas flooded hood, or deposition can take place in an atmospherically controlled chamber. The WAAM process has a much higher deposition rate than most other metal additive manufacturing techniques (up to 10 kg/h). It also provides better material utilization than powder based methods [9–12], but is restricted to wider wall thicknesses and cannot produce as fine scale features. This low cost process is therefore most suited to producing larger scale parts with less complex geometries.

The α–β titanium alloy, Ti–6Al–4V, is the 'work horse' of the aerospace industry and widely used in airframe and aeroengine applications, where the production of near-net shape components by AM can result in significant cost savings. However, a current concern with AM using this alloy is that coarse primary columnar β grain structures are nearly always observed to be produced in the consolidated material. This undesirable grain structure is seen across a wide range of AM platforms [6, 9–16]. With wire based AM the primary β grains are often as tall as the build height and with larger components can be tens of centimetres long [9–16]. This strong tendency to form coarse-columnar β grain structures in AM with Ti–6Al–4V is difficult to avoid because it results from a combination of the solidification conditions in a small heated moving melt pool, where there is a steep positive thermal gradient at the solidification front, and the metallurgical characteristics of the alloy itself [13–16]. In particular, the Ti–6Al–4V alloy system does not

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lend itself to nucleation ahead of the solidification front because of the high partition coefficients of aluminium and vanadium, which are close to one, and the lack of suitable grain refining particles in the melt [17]. These process and metallurgical limitations restrict the degree of constitutional supercooling that can occur so that, when combined with a lack of melt inoculants, nucleation ahead of the solidification front is difficult to achieve [13–16].

Although in AM the β grain structure developed during solidification transforms to a fine α and retained β lamellar structure on cooling below the β-transus temperature, the microstructural memory of the coarse, directional, primary-β microstructure can still have a significant impact on mechanical performance. In particular, directional growth of large primary β grains generally produces a strong <001> fibre texture, which gives rise to a related α transformation texture [13–16] and this can potentially result in texture clustering of aligned α-plates within the β matrix. Such factors are known to be detrimental to fatigue life [18, 19] and can contribute to mechanical anisotropy [20–22]. In addition, with a coarse primary β grain structure, grain boundary α can cause premature failure in transverse loading [21, 23]. However, to date, little systematic work has been published on the texture found in AM titanium components produced by wire-based techniques like the WAAM process.

Potential methods for refining the poor primary grain structure seen in AM deposits include; i) modification of the solidification conditions in the melt pool, through manipulation of the process variables [10], or ii) altering the alloy chemistry [17, 24, 25]. However, in AM there is limited scope for changing the process window, because this is dictated by the conditions required to obtain stable part dimensions [9, 10]. Furthermore, while trace additions of elements like boron are known to act as growth restrictors in titanium [25] this can have negative consequences through the formation of brittle second phase particles (e.g. TiB).

In the present work an alternative approach has been investigated for improving the large columnar β-grain structures and strong textures typically seen in wire-based AM processes. This has involved the introduction of a small deformation step sequentially with the deposition of each layer. The deformation step was applied using a roller integrated with the AM system, so that each deposited layer could be lightly deformed before adding a new layer of material (Fig. 1). Although this set up limits the technique to simpler geometries, the aim of this approach was to see if it was possible to introduce sufficient plastic deformation into each layer so that refinement of the β-grains could occur during re-heating, when the next layer was deposited. It was also hoped that this might generate a weaker texture, which would lead to more isotropic mechanical properties [18, 19, 26]. Although the introduction of a light rolling step in AM will moderately reduce the rate of build-up of material and causes a slight spreading in the wall width, this can be controlled in an automated manufacturing system and would not be a major issue when building relatively simple component designs. In fact, it has been found that rolling increases the accuracy of the wall dimensions, by correcting variation in the wall width caused by the bead profile [27]. There are also other potential methods available for applying deformation to each layer in AM that are not so restricted by geometry, such as by peening [28]; hence the efficacy of this novel approach is of more general interest.

It should be noted that in this collaborative study the concept of the hybrid WAAM deformation process was developed by Cranfield University Welding Engineering Research Centre [27, 29], who have previously published work investigating the effect rolling has on the residual stress within the builds [27], and noting the effect on the refinement of the microstructure [30]. The current work, performed at Manchester University, is complementary in that it investigates the effect the refinement has on the primary β and final α texture, and goes into more detail than the previously into the mechanism of formation and the distribution of the refined β grain structure.

2. Experimental

2.1. WAAM samples

The undeformed and rolled WAAM samples were built using a Ti–6Al–4V alloy welding wire (1.2 mm diameter) with a titanium base plate of the same alloy. The substrate material was a conventional hot rolled and annealed plate that had a recrystallized equiaxed α–β microstructure [18]. The samples studied were produced under identical conditions — as one meter long, 20 layer high, straight, vertical walls, using a pulsed GTAW welding system with an average current of 110 A. Each

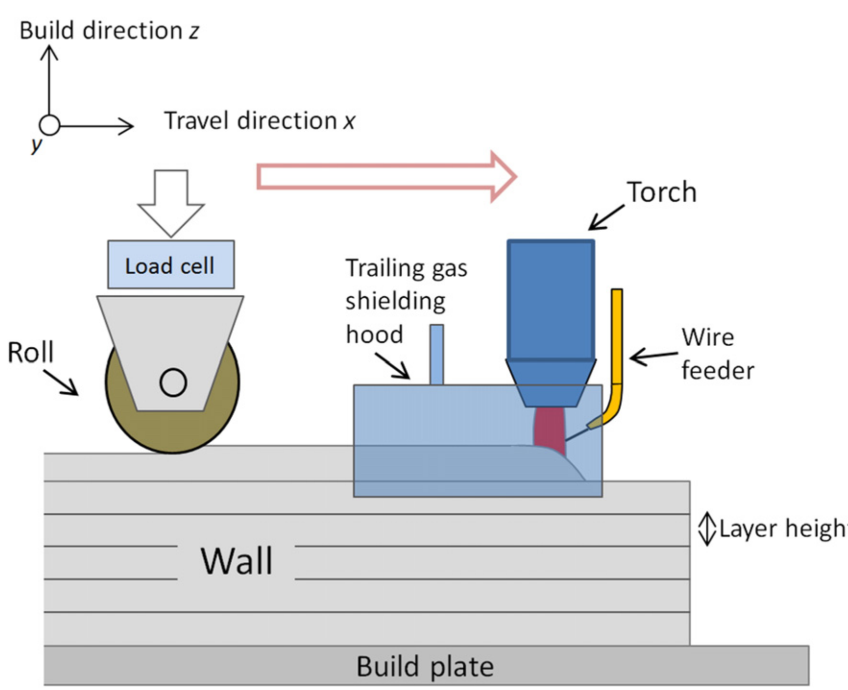

Fig. 1. Schematic diagram of the combined WAAM rolling process.