Interpass rolling of Ti-6Al-4V wire + arc additively manufactured features for microstructural refinement

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\textbf{ABSTRACT}

In-process deformation methods such as rolling can be used to refine the large columnar grains that form when wire + arc additively manufacturing (WAAM) titanium alloys. Due to the laterally restrained geometry, application to thick walls and intersecting features required the development of a new ‘inverted profile’ roller. A larger radii roller increased the extent of the recrystallised area, providing a more uniform grain size, and higher loads increased the amount of refinement. Electron backscatter diffraction showed that the majority of the strain is generated toward the edges of the rolled groove, up to 3 mm below the rolled surface. These results will help facilitate future optimisation of the rolling process and industrialisation of WAAM for large-scale titanium components.

\section{1. Introduction}

Wire + arc additive manufacturing (WAAM) is a 3D printing technology capable of meeting the needs of industry for producing metre-sized metallic components \cite{1}. These components are produced through layer by layer material deposition, utilising an arc-based heat source, such as plasma or Metal Inert Gas deposition, and wire as feedstock \cite{2,3}. Fig. 1 illustrates the process.

Owing to the many benefits of WAAM (e.g. high deposition rate, manufacturing cost reduction and reduced lead time) it is finding increasing interest for the manufacture of aircraft structural components – particularly for Ti-6Al-4V. This is primarily due to titanium and its alloys being extremely expensive in terms of purchase cost (> £70 kg\textsuperscript{-1}), energy consumption (> 500 MJ kg\textsuperscript{-1}) and CO\textsubscript{2} emissions (> 40 kg kg\textsuperscript{-1}) \cite{4}. Typically, Ti-6Al-4V aircraft structural components are machined from oversized ingots, forgings and extrusions. Not only is this a time consuming process (e.g. waiting for forging dies to be manufactured) but it is also expensive due to the proportionally large amount of material that is purchased compared to the amount that remains after machining. The buy-to-fly (BTF) ratios of components manufactured using this approach can be as poor as 20:1. WAAM reduces the material required to make a component by producing near-net-shape preforms, which are subsequently machined to the desired dimensions. This brings substantial improvements to the BTF ratios (typically 1.5), which significantly reduce the manufacturing cost \cite{2}.

For successful implementation of WAAM the material properties should ideally meet or exceed those from the wrought material. This can be difficult due to the very different manufacturing route that AM parts undergo – normally they experience a series of thermal cycles with ever decreasing peak temperatures. For Ti-6Al-4V WAAM the small freezing range and epitaxial growth results in large, columnar prior β grains that have anisotropic properties, which are undesirable for aerospace applications \cite{2,5}.

Colegrove \text{et al.} \cite{6} described how interpass rolling of the deposited layers can improve the mechanical properties of Ti-6Al-4V WAAM deposits through microstructural refinement of the prior β grains. Interpass rolling increased both the yield and tensile strengths by 18–25% while eliminating material anisotropy. An equiaxed prior β microstructure that can be as small as 60 μm is produced despite the induced strain being relatively modest (7–20%) \cite{9,10}. Interpass rolling also improves fatigue properties due to the high proof strength, fine Widmanstatten basket-weave microstructure and isotropic texture with a small prior β grain size \cite{6,7}. The improvement may also be due to the reduced incidence of porosity \cite{8} which is known to limit fatigue performance \cite{9}.

An early investigation showed that prior β refinement initiates on...
twinned α colonies upon heating [10], but more recent work reports that the new β orientation originate from twinned β cells; because the β phase grows from residual β between the α laths before new β can nucleate in pure (i.e. twinned) α at higher temperature [11]. The large number of β nuclei with random orientation prevent the re-establishment of the previous columnar microstructure.

A number of different rolling methods have been developed. Interpass rolling has predominantly been applied to thin (< 10 mm) walls and the rollers often have a similar profile to the deposit [7,12] (Fig. 3(a)). Martina et al. [7] demonstrated that similar levels of refinement were possible with a flat roller, however the grains were smaller in the centre of the wall due to the concentration of strain in this region. Applications that involve thin walls have very little lateral restraint, so strain can be relatively easily induced within the material:

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Fig. 1. Illustration of the WAAM process.

Fig. 2. A macrograph of a thick Ti-6Al-4V WAAM wall that was rolled with a flat roller at 75 kN. Notice that there is little prior β grain refinement.

Fig. 3. Schematic diagram of the main rolling methods: (a) vertical with a profiled roller; (b) rolling with an inverted profiled roller for thick sections and intersections.
a large vertical plastic compressive strain produces an almost equal in magnitude and tensile lateral strain. Zhang et al. [13] and Zhou et al. [14] applied the technique ‘in situ’ to thin steel walls, and also achieved significant levels of grain refinement. Xie et al. [15] demonstrated the application of pinch rollers which were applied just prior to a flat roller. The equipment was termed ‘a miniature metamorphic rolling mechanism’ and it allowed accurate and flexible control of the final part geometry. Finally, Hönnige et al. [16] applied side rolling to Ti-6Al-4V walls: after the wall was built it was rotated onto its side and it was deformed with a large flat roller, which was extremely effective for removing residual stress and distortion.

A preliminary investigation into the rolling of a thick (approximately 18 mm wide) wall with a flat roller was conducted at Cranfield University. As shown in Fig. 2, application of a 75 kN load did not produce any significant grain refinement due to the greater level of lateral restraint with this geometry. i.e. it is difficult to induce the required strain for microstructural refinement. Consequently, in this paper we investigate whether an inverted profile roller – as shown in Fig. 3(b) – generates the large strains required for grain refinement. This will be applied to intersections and thick walls produced by WAAM and are contained in most applications.

2. Methodology

The work was done in three parts: the first involves the production of “thick” Ti-6Al-4V walls; the second involves the production of intersecting features; and finally electron beam back scattered diffraction (EBSD) was used to generate strain maps of the rolled material. The purpose of the EBSD work is to aid understanding of how the rollers impart strain into the samples.

2.1. Thick walls

The samples were manufactured on the HiVE (High-Value Engineering) centre at Cranfield University: a roller is placed in the spindle of a large CNC machine which allows multi-directional rolling with loads up to 100 kN. This machine is shown in Fig. 4 and is also equipped with plasma deposition equipment that allows the wire to rotate around the torch to facilitate deposition in multiple directions. A preliminary investigation into the rolling of a thick (approximately 18 mm wide) wall with a flat roller was conducted at Cranfield University: a roller is placed in the spindle of a large CNC machine which allows multi-directional rolling with loads up to 100 kN. This machine is shown in Fig. 4 and is also equipped with plasma deposition equipment that allows the wire to rotate around the torch to facilitate deposition in multiple directions. A preliminary investigation into the rolling of a thick (approximately 18 mm wide) wall with a flat roller was conducted at Cranfield University: a roller is placed in the spindle of a large CNC machine which allows multi-directional rolling with loads up to 100 kN. This machine is shown in Fig. 4 and is also equipped with plasma deposition equipment that allows the wire to rotate around the torch to facilitate deposition in multiple directions. A preliminary investigation into the rolling of a thick (approximately 18 mm wide) wall with a flat roller was conducted at Cranfield University: a roller is placed in the spindle of a large CNC machine which allows multi-directional rolling with loads up to 100 kN. This machine is shown in Fig. 4 and is also equipped with plasma deposition equipment that allows the wire to rotate around the torch to facilitate deposition in multiple directions. A preliminary investigation into the rolling of a thick (approximately 18 mm wide) wall with a flat roller was conducted at Cranfield University: a roller is placed in the spindle of a large CNC machine which allows multi-directional rolling with loads up to 100 kN. This machine is shown in Fig. 4 and is also equipped with plasma deposition equipment that allows the wire to rotate around the torch to facilitate deposition in multiple directions.
same and two types of intersections were manufactured: a cruciform and a tee. The intersections were composed of 16 mm wide and 20 mm high walls deposited with an oscillation strategy on 180 mm × 180 mm × 12.7 mm substrates – see Fig. 6. The deposition paths involved depositing first the black wall and then, the red and green walls. At the intersecting area the wall width was increased to 22 mm to widen the material overlap enabling a radii to be machined for the final part. The dimensions of the path are shown in Fig. 6 and the path was reversed every second layer to obtain a flat intersection that assisted the subsequent rolling process. Due to the proprietary nature of these parameters, they cannot be disclosed; however they produced a layer height of approximately 1.5 mm and a bead width of approximately 6 mm. Local shielding was used as for the previous experiments.

Table 3 summarises the rolling strategies used for the cruciform and tee intersections:

<table>
<thead>
<tr>
<th>Intersection type</th>
<th>Intersection label</th>
<th>Rolling strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cruciform Intersection</td>
<td>CSX</td>
<td>Unrolled</td>
</tr>
<tr>
<td></td>
<td>R1X</td>
<td>One rolling pass</td>
</tr>
<tr>
<td></td>
<td>R2X</td>
<td>Two rolling passes</td>
</tr>
<tr>
<td>Tee Intersection</td>
<td>CST</td>
<td>Unrolled</td>
</tr>
<tr>
<td></td>
<td>R1T</td>
<td>One rolling pass</td>
</tr>
<tr>
<td></td>
<td>R2T</td>
<td>Two rolling passes</td>
</tr>
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Fig. 5. Roller types used for the experimental study.

Fig. 6. Deposition paths for the (a) cruciform and (b) tee intersections. Note direction of deposition is alternated every second layer.

Fig. 7. Schematic of the extraction for the plastic strain measurement specimen and location of the profiled rolling pass.
Two rolling strategies were carried out: with one and two rolling passes. In each case a rolling load of 75 kN at a speed of 2000 mm/min was applied with the 3 mm radius roller shown in Fig. 5. The single rolling pass was applied to the centreline of the deposit, while the two rolling passes were done parallel to each other and offset from the centreline by 3 mm, leaving a 6 mm gap between the two rolling passes. Every layer the rolling path directions were reversed and it was applied after the deposit was near room temperature (< 100 °C).

For the metallographic analysis, a sample was extracted from a planar cross-section of each intersection. Analysis of the sections was identical to the thick wall samples in 2.1.

### 2.3. EBSD and strain mapping

A 20 mm wide, 15 mm high and 80 mm long section of an unrolled and stress relieved (4 h at 650 °C in an inert atmosphere) Ti-6Al-4V wall was extracted, as shown in the schematic in Fig. 7. One rolling pass along the centreline on the top surface of the specimen was produced using the R3 roller with 90 kn. The measured surface was located in the y-z plane in the centre of the specimen.

After mounting in conductive resin, the surface was treated with similar sample preparation to that already mentioned, including polishing, but without etching. Scanning electron microscopy (SEM) and electron back scatter diffraction (EBSD) were used to produce the inverse pole figure (IPF) map of the α-phase, using the Maxim FEG-SEM by CamScam and the Aztec acquisition software to process the data from the Oxford instruments EBSD system. To incorporate the 4 mm wide roller groove and the estimated depth of the penetration, an area 6.37 mm wide and 4.82 mm high was scanned with an EBSD step size of 6 μm in the top centre of the 20 mm by 15 mm cross-section. The Ti-6Al-V alloy typically contains a low volume fraction of only 5–9% of the high temperature bcc β-phase [18]. Davies et al. [19,20] have developed a procedure that can reconstruct the IPF of the parent β-phase at elevated temperatures, using the Burger orientation relationship (BOR). According to BOR the hexagonal close packed (hcp) α-phase transforms with the basal {0001} plane upon cooling on the most densely packed {110} plane of the parent body-centred-cubic (bcc) β-phase. The detailed β-reconstruction procedure is explained elsewhere [21].

To identify the region that each of the rolling passes deforms plastically, a plastic strain map was produced using the compiled EBSD data. They were produced using information from the regions where the previously explained β-reconstruction was not successful: after performing the β-reconstruction procedure six times with gradually changing tolerated deviation angle between 1° and 6° of neighbouring α-laths [22], certain areas could not be reconstructed. A high tolerance angle during the application of the technique allows the reconstruction of more parent β-phase orientations, while a small tolerance can only reconstruct regions with only little deviation of neighbouring α-laths. Since plastic strain is responsible for deviation within the α-colonies,
the unresolved regions of the six β-reconstructed IPF maps were merged into map regions with relatively low to relatively large deviation, representing the plastic strain density. This strain mapping technique based on EBSD β-reconstruction is also explained in more detail in Donoghue et al. [23], who applied this technique successfully to rolled Ti-6Al-4V WAAM walls.

3. Results and discussion

3.1. Thick wall microstructural observations

In Fig. 8, the microstructures of the unrolled sample and a rolled sample are compared. The results clearly show that significant recrystallisation and refinement of the prior β grains occur when the inverted profile rollers are used to deform the samples. The prior β grain size results are plotted in Fig. 9. The reason why rolling is believed to refine the columnar β-grains, as originally reported elsewhere [6], is due to the rolling process generating new β orientations that are able to out-compete growth from the residual β upon reheating above the β transus, thus breaking the columnar grains.

Interestingly, the results in Fig. 9 show that the mean recrystallised grains are larger when a roller with a smaller contact area is used. This phenomenon can be explained by the pressure generated by the rollers. For the smaller radii the pressure was more localised causing a thinner band of recrystallized material. Consequently when the Planimetric Method was used to calculate the mean grain size many larger grains outside of the directly recrystallised area were included in the calculation, which increased the mean grain size calculation. Regardless of the roller type used it can be clearly seen that more recrystallization occurs with larger applied forces.

3.2. Intersection microstructural observations

Photographic images of the cruciform and tee intersections are shown in Fig. 10. Very little surface oxidation was observed (as indicated by surface discoloration) as a consequence of slow deposition and use of the local shielding device which minimised surface oxidation. As an aside, the oxygen content of the thick wall described in Section 3.1 which was also built with the local shielding device indicated that it was between 0.17 (inside) and 0.18 (outside) which was within the 0.12-0.18% limit in the specification for the supplied wire (Table 1). Well-formed intersecting WAAM features that have a uniform layer height are difficult to obtain and require careful control of the deposition parameters around the intersection in particular.

Some of the photos from the metallographic analysis are presented in Fig. 11. As-deposited WAAM titanium is characterised by coarse
columnar prior β grains that grows epitaxially across the layers; cut samples show the microstructure across the growth direction of the columnar grains (see Fig. 11(a) and (b)). The strain induced by rolling and the heat treatment due to the deposition of the next layer, causes refinement of the grains, as shown in Fig. 11(c) and (d).

The average prior β grain size for the rolled samples is shown in Fig. 12. Please note that due to the columnar grains in the control samples being comparatively large, their mean grain sizes are not displayed (1.28 mm² and 1.16 mm² for the tee and cruciform, respectively). Comparing the results shows that the second roller pass achieves an average grain size reduction of 67.3% for the tee intersection and 65.7% for the cruciform intersection compared to the single pass rolling strategy. In addition, the average grain size values are slightly smaller in the cruciform intersection compared to the tee intersection. The cooling rates with this geometry are likely to be slightly greater due to the greater heat sink caused by the larger amount of material around the intersecting feature. The greater cooling rate produces a more refined microstructure [25]. Fig. 12 also shows that the variation of the grain size was reduced with two roller passes, as evidenced by the smaller error bars.

Higher magnification images of the unrolled and rolled cruciform intersections are shown in Fig. 13 and Fig. 14, respectively. The grain size is not uniform across the intersections that were rolled, although, as previously stated there was less variation when two roller passes were applied. The smallest grains are found where the rolling paths cross (Fig. 14(c) and (e)); while the largest grains are outside the rolled region (Fig. 14(b)); and there is a slight grain size increase between the roller paths Fig. 14(d). Similar results were obtained for the tee intersection.

3.3. EBSD and strain mapping

The EBSD maps are shown in Fig. 15. The IPF of the α-phase (Fig. 15(a)) shows that most of the anisotropic hcp crystals are...
predominantly oriented with the \(\{110\}\) or the \(\{102\}\) plane normal to the build direction \(z\). These two dominant alignments are typical for Ti-6Al-4V WAAM [23]. Fig. 15(b) is an example of the reconstructed \(\beta\)-IPF using 3° deviation tolerance. At the black spots, the reconstruction was not successful, since the deviation was greater than 3°. The plastic strain map is shown in Fig. 15(c). The incremental colouration shows mismatches of neighbouring \(\alpha\)-laths as a deviation angle [°] from fulfilling the ideal BOR during \(\beta\)-reconstruction, where a greater angle represents qualitatively a larger plastic deformation. The largest deformation appears at the edges of the rolled groove and reaches a depth of approximately 3 mm. In the centre of the groove at the interface with the roller, a small region of little plastic deformation can be seen, which is where the friction between roller and surface prevented the material from local straining. This effect has been reported elsewhere [26].

This plastic deformation is desired, as it is required to provide the grain refinement, triggered by the re-heating above \(\beta\)-transus during the deposition of the subsequent layer. Therefore, if the HAZ of one layer overlaps with the region that has been plastically deformed during the previous rolling step, the microstructure will be refined. It should be noted that the EBSD maps don’t show the actual plastic strain, but indicate qualitatively the local strain density.

No noteworthy plastic deformation occurs outside the edges of the groove in the transverse \(y\)-direction, i.e. the width of the rolled groove is the same as the width of the plastic deformation within the material. Therefore, for the path planning of multiple rolling passes the following conclusion can be drawn: for a comprehensive strain induction and homogeneous grain refinement, the step distance of parallel rolling passes should be equal to the width of the groove, produced by a single rolling pass.

The deformation produced by the roller needs to be sufficiently

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Fig. 14. Microstructure of the cruciform intersection rolled with two roller passes. Note that the arrows show the location of the roller passes.
large to extend into the heat affected zone of the next deposited layer. i.e. deformation at the surface is of little value because it will be melted with the next deposited layer. Fig. 10(b) shows that the banding in the depth indicated in Fig. 15. Subsequent studies will explore the relationship between the location of the deformed material and the heat treatment from the next deposited layer.

4. Conclusions

Results from this research have significant benefits in the development of the wire + arc additive manufacturing (WAAM) technology for the production of aerospace components. This study proves:

• Grain refinement can be achieved via interpass rolling of wide walls and intersecting WAAM features through the application of an inverted profiled roller.
• The different roller types and applied forces have a significant effect on the mean grain size and distribution. The larger rolling forces produced more refinement, while increasing the radius of the roller protrusion increased the extent of the recrystallised area.
• EBSD strain maps showed that the majority of the strain is generated towards the edges of the rolled groove and up to 3 mm below the rolled surface – where it was needed for grain refinement.
• Since the width of the strained region and the groove are almost identical, a uniformly refined microstructure is likely to be produced by setting the step distance equal to the width of the rolled groove.

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References

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